Profit Oriented Multichannel Resource Management of Integrated Communication and Broadcast Networks

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Abstract**—**Broadcast networks are potential for carrying services with both high data rate and high mobility. Combined with other media as return channels for user requests and acknowledgement signaling, broadcast networks can provide interactive data services too. This paper proposes a multichannel architecture for Integrated Communication and Broadcast Networks (ICBN) which employs all redundant available broadcast bandwidth to provide huge access bandwidth for multimedia information delivery while in fast moving. This architecture can be a highly recommendable candidate of future 4G/5G communications. Most existing bandwidth management policies focus on single channel bandwidth distribution over different data flows, and no multichannel bandwidth management policies for ICBN are found yet. In order to fully employ all channels, a Profit Oriented Bandwidth Allocation Method (POBAM) is given for real-time multichannel bandwidth management. Analytical and simulation results show that the POBAM can exploit the multichannel resources for near global profit maximization, and provide effective QoS differentiation as well. In addition, the joint channel management outperforms the separate channel management greatly. The complexity of the POBAM is low enough for on-line multichannel bandwidth management even when the scale of ICBN is quite large.

Index Terms**–** integration, resource management, multichannel, bandwidth allocation

I. Introduction

The convergence of telecommunication networks and broadcast networks will help providing broadband multimedia information delivery while in fast moving. This technology is crucial for business-class users who want to have multimedia information access anywhere and anytime. Neither the traditional telecommunication networks and/or computer networks (even though mobile Internet) nor digital broadcasts network can satisfy this needs independently. Specifically, the telecommunication/computer networks are good for interactive communications, but it is not easy to realize a broadband communication while in fast moving. On the other hand, digital broadcast networks are suitable for large-volume broadband information delivery, but not good for interactive communication. Hence, their convergence is crucial. For example, Digital Terrestrial Video Broadcasting (DVB-T) system is an ideal carrier for mobile receptions([1]), and integration of DVB-T and Internet will make possible that users at high speed are able to access the Internet with high data rate. One of the most challenging issues in the Integrated Communication and Broadcast Networks(ICBN) is how to deal with the feedback information. This can be solved by using some kind of out-of-band feedback channels for the uplink as a return channel for user requests and acknowledgement signaling. Most other access systems like GSM/GPRS, WCDMA and so forth can be used for this purpose.

Quite a huge part of the Internet services like information or software download are one way, and are accessed mostly by a large number of users simultaneously without any individual preferences. So ICBN is a convenient and cost-effective solution for distributing Internet resources to users, especially those sharing common interests like traffic reports, tourist information, share-list and so forth. In ICBN, the major traffic will be the downlink broadcast TCP/IP packets to the mobile terminals. Since the broadcast IP packets are in general in a big traffic volume, how to efficiently allocate the radio resource as well as schedule the packet transmissions are of great importance. In particular, the broadcast IP packets are usually generated in bursts and may also be with diverse QoS requirements; therefore dynamic radio resource allocation schemes with QoS guarantee are crucial. Besides, due to the big cell size and large coverage, traditionally, it is considered that broadcast networks can only provide very limited system capacity measured by the number of users that can simultaneously access Internet through ICBN. Hence the allocation of the valuable access bandwidth has been carefully designed in recent researches. [2] gives a rate control coding mechanism for DTV, while [3] designs a rate schedule method for IP data transmissions. Both of them work exclusively for either DTV or IP services, and may not be effective when DTV and IP services coexist. [4] makes some improvement and presents a single channel dynamic bandwidth allocation algorithm for

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transmissions combining DTV and IP traffic. These algorithms work well sometimes. But, they are lack of the capability to provide QoS differentiated services to users with different priorities who pay accordingly. Besides, their algorithms are fit only for single channel bandwidth scheduling.

Considering the combination of DVB-T and Internet as an instance, this paper proposes a multichannel architecture of ICBN which exploits redundant bandwidth generated by stuffing packets in all available broadcast channels to provide enormous access bandwidth, and overthrows the traditional view that only very limited system capacity can be provided by ICBN. As the best we know, no multichannel bandwidth management policies for this kind of implementation of ICBN exist yet. Hence, we present a novel approach for multichannel bandwidth allocation in ICBN with rather low complexity to allocate the bandwidth with effective QoS differentiation and to maximize the economic profit of the system resource utilization.

II. Design of ICBN with Multiple Channels

Originally, one analog TV program occupies the whole 8 MHz channel. By digitalization, the transmission robustness will be greatly enhanced for mobile reception, and several programs can be multiplexed into one channel, which greatly improves the capacity of TV programs and may produce a great redundancy of DTV channels.The transmission data rate is constant based on the physical layer mode used. In order to get a fixed data rate, e.g. 38Mbit/s per 8 MHz channel, stuffing packets are inserted. These stuffing packets can be exploited as a carrier for additional data transmission services without injuring the DTV programs in the channel. There are two ways for data transmission: the bandwidth unused by DTV programs; and the full channel can be used for data services.

Traditional researches have considered the situation that each DTV channel supplies additional data services separately, and single channel bandwidth management policies have been designed([2], [3], [4]). However, in each DVB channel, the compression of video and audio data of DTV programs causes a variable data rate, since pictures with fierce motions will be encoded with higher data rate than those with less motions. So the available bandwidth for additional data services varies from time to time. Hence, the available resources for broadband Internet access services dynamically distribute in all DVB channels, which can be called channel diversity. Besides, the bandwidth requests of the users vary from time to time, which can be called user diversity. Users that can not be satisfied by one channel may get the required bandwidth from other channels. The effective exploitation of both the channel diversity and the user diversity will make full use of all DVB resources for Internet access services, and this statistical multiplex will greatly improve the system performance. So we propose a multichannel ICBN architecture which combines DVB-T and Internet to provide broadband access services to users with high mobility.

This multichannel architecture of ICBN is concisely illustrated in Fig.1, where five users either stationary or mobile are listed for explanation. Through the return channel which can be a third medium like WCDMA (dashed lines between user terminals and policy executor in Fig.1), the customer gives some Internet service request to the radio station. The station would then be in charge of downloading the required content from remote ISP, and decide the allocation of DVB-T multichannel resources to each IP stream according to user QoS requirement. Then IP data will be scheduled to broadcast to the customers. IP data to be transmitted will be multiplexed together with live/recorded DVB programs in the multiplexer. The DVB transport stream will then be broadcasted to the users through the terrestrial radio tower.

Though limited bandwidth is available in one DTV channel for additional data services, and if only one channel is exploited, the application would be very limited and the system capacity would be rather small. However, the frequency band for broadcast is large and there are dozens of DTV channels. If many or even all the DTV channels are exploited for Internet access services, that would result in huge wireless access bandwidth in each cell, especially when some DVB channels are fully used for additional data services. The joint management of all the channels' bandwidth available for data transmissions would further improve the system throughput for Internet broadband access services. Hence, we propose to jointly manage all available broadcast channels for additional access services. In the following part, we'll model the problem of multichannel bandwidth management in ICBN, and give an efficient algorithm, named as Profit Oriented Bandwidth Allocation Method (POBAM), to achieve near-global-optimal allocation result for system profit maximization and to provide differentiated QoS to different users.

III. Multichannel Scheduling Modeling and Profit Oriented Bandwidth Allocation

A. Problem Modeling

Assume that M digital broadcast channels are used for additional data services. The reallocation of the bandwidth will be executed when some existing flow has finished its transmission or a new connection needs to be established, which means that the bandwidth reallocation will not happen too frequently. At the reallocating time, K users are applying for Internet accesses with certain bandwidth requests. Because the capability for terminals to be able to receive signals from more than one broadcast channel simultaneously would greatly add the receiver complexity, and even for a terminal that supports multichannel signal receiving simultaneously, the terminal can be treated as several terminals, each of which can receive signal of only one channel at a time and will compete for the bandwidth allocation in the radio station independently. Hence, each user terminal is assumed to be able to receive signal from only one broadcast channel at a time for simplicity. During the bandwidth allocation, all users will either be rejected for lack of sufficient bandwidth or be accepted with supply of full required bandwidth.

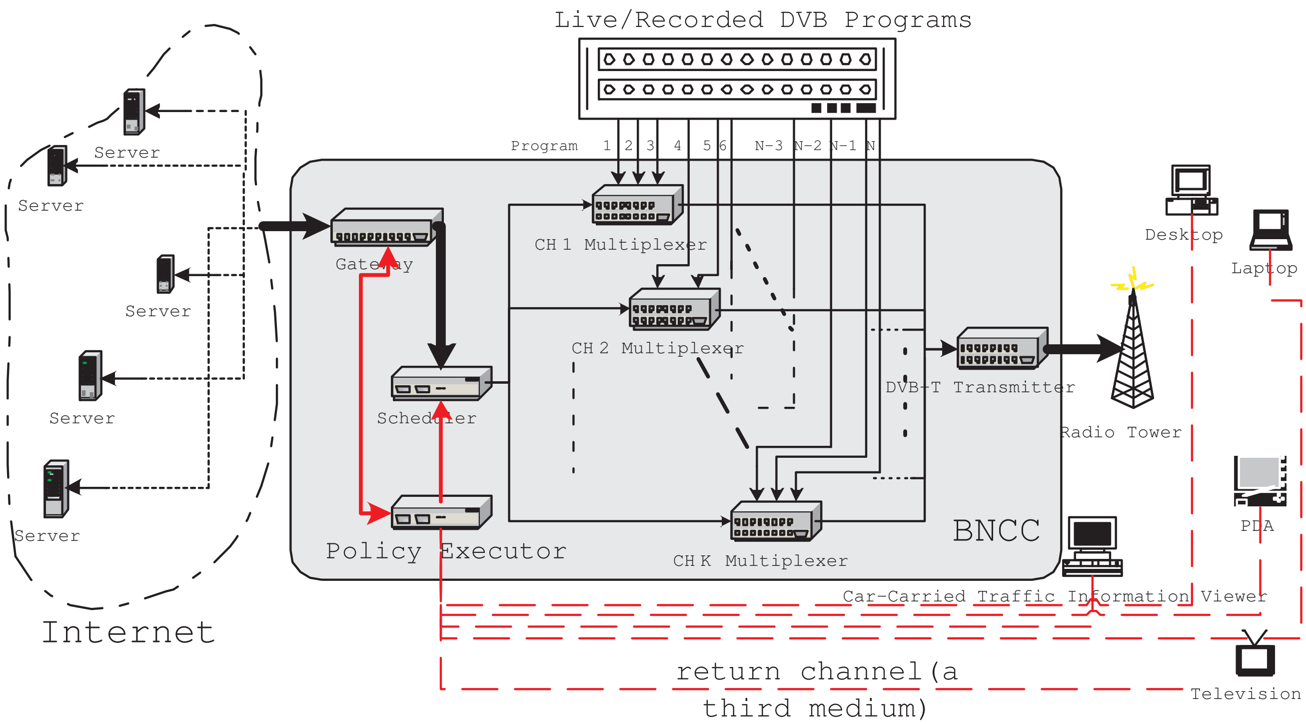

Fig. 1. Multichannel Architecture of Integrated Internet and DVB-T Network

Define the allocation matrix Δ as:

$$\Delta = \begin{pmatrix} \delta_{11} & \delta_{12} & \dots & \delta_{1M} \\ \delta_{21} & \delta_{22} & \dots & \delta_{2M} \\ \vdots & \vdots & \ddots & \dots \\ \delta_{K1} & \delta_{K2} & \dots & \delta_{KM} \end{pmatrix}^T, \tag{1}$$

where δ_{ij} is the allocation factor with $\delta_{ij} = 1$ if user i is included in channel j and $\delta_{ij} = 0$ otherwise.

The allocation policy should rely on how much users pay for their services. Suppose that user i requests B_i bandwidth with unit bandwidth cost C_i, i.e. the price user i pays for unit bandwidth is C_i. Our purpose is to maximize the profit the system earns through the bandwidth allocation. The allocation should try to pick a proper selection of all active users and then distribute the selected users to the proper channels to make full use of all available broadcast channel resources and maximize the system profit. The problem is formulated in (2):

$$\max Profit(\Delta) = \max \sum_{i=1}^{K}\sum_{j=1}^{M} B_i C_i \delta_{ij},$$
$$s.t. \begin{cases} \delta_{ij} \in \{0,1\},\ i = 1,\dots,K, j = 1\dots M \\ \sum_{j=1}^{M} \delta_{ij} \in \{0,1\}, i = 1,\dots,K \\ 0 \le \sum_{i=1}^{K} B_i \delta_{ij} \le R_j,\ j = 1,\dots,M \\ R_j = \hat{R}_j - \sum_{l=1}^{n_j} \hat{R}_{jl}, j = 1,\dots,M \end{cases}, \tag{2}$$

in which $\hat{R}_j$ is total bandwidth in channel j, n_j is the number of DTV programs contained in channel j, $\hat{R}_{jl}$, for $l = 1,\dots,n_j$, is the bandwidth for transmitting the lth program, and hence R_j is the available bandwidth for additional IP data transmissions in the jth channel. The second constraint corresponds to the assumption that user terminals supports signal reception of only one channel at a time, and shows that data for one user can only be transmitted by one channel after the bandwidth allocation.

In order to avoid trivial cases, assume that:

$$\max_{i=1,\dots,K} B_i \le \max_{j=1,\dots,M} R_j, \tag{3}$$
$$\min_{j=1,\dots,M} R_j \ge \min_{i=1,\dots,K} B_i, \tag{4}$$
$$\sum_{i=1}^{K} B_i \ge \max_{j=1,\dots,M} R_j \tag{5}$$

the first assumption(3) ensures that each user i with bandwidth request B_i can be satisfied at least by one channel as otherwise it may be removed from the problem. If the second one(4) is violated, the channel with the smallest available bandwidth may be discounted as no user can be satisfied by it. The last inequality(5) avoids a trivial solution where all users can be satisfied by the channel with the largest capacity.

The multichannel allocation program of (2) is found to be a typical 0/1 Multiple Knapsack Problem (MKP) ([5]), which can be seen as a combination of the well known Knapsack Problem (KP) ([6]) and Bin Packing Problem(BPP) ([7]), both of which are NP-complete. Hence MKP is also NP-complete with exponential time bounds ($\mathcal{O}(2^{KM})$ in our problem). Therefore, exact search algorithms like branch-and-bound algorithms ([8],[9]) that lead to globally optimal solutions are too time-consuming and can only be applied to very small MKP problems. Recent algorithms based on metaheuristics have been developed to obtain competitive results on large similar instances($K = 300, M = 25$), e.g. simulated annealing ([10]), tabu search ([11],[12]) and genetic algorithms ([13],[14],[15]). Among these algorithms, the genetic algorithms show better efficiency and convergence speed. Here, for the purpose of comparison in the simulations, we outline the genetic algorithm proposed in [15]:

1.Initialization: Generate random allocation matrixes as the genetic codes. The number of genetic codes is decided by the population size.

2.Offspring Selection:Calculate the fitness of each genetic code according to the fitness function (Eq.(4) in [15]). If the mean fitness has converged to a certain degree or the maximum generation has reached, cease all the operations and pick out the best genetic code as the final result, then return. Otherwise, select the offspring according to the fitnesses based on Roulette Wheel selection.

3.Crossover: Do the crossover operations and recombine all the genetic codes pair by pair.

4.Mutation: With some small probability (mutation rate), flip each bit in the offspring. Goto **Offspring Selection**.

Though metaheuristical methods work well some times, these methods must run sufficient iterations to get satisfying results, hence they can only work off-line and are not feasible for real-time applications. However, in our bandwidth allocation problem, the bandwidth must be allocated on-line, and the problem may be extremely large, e.g. 83 8MHz joint channels and 1000 active users. Hence, an algorithm with low complexity and good performance is needed. One natural idea is to disregard the joint channel bandwidth management, and allocate the bandwidth in each channel separately, i.e. fill each channel one by one until either all users have been served or all channels have been used. We refer to this method as the separate channel scheduling. Obviously, this method has rather low complexity. However, the performance is very poor, and we need to design an effective joint channel bandwidth allocation algorithms to maximize the system performance.

In the following subsections, the upper bounds of the problem is given, and a novel algorithm that can supply near-global-optimal results with low complexity for large scale instances requiring real-time bandwidth allocations is presented.

B. Upper Bounds

Relax the first constraint $\delta_{ij} \in \{0,1\}$ in (2) to $0 \le \delta_{ij} \le 1$ ($i = 1,\ldots,K, j = 1\ldots M$). [16] proved that the objective value of an optimal solution to the linear relaxed MKP is the same as that of an optimal solution to the linear relaxed SMKP (Surrogate relaxed MKP), which can be transformed to the following ordinary 0-1 Knapsack Problem([17]):

$$\max Profit(\Delta) = \max\{\sum_{i=1}^{K} B_i C_i \delta_i^{'}\},$$
$$s.t. \begin{cases} \delta_i^{'} \in \{0,1\},\ i = 1,\ldots,K \\ 0 \le \sum_{i=1}^{K} B_i \delta_i^{'} \le R. \end{cases}, \tag{6}$$

where $\delta_i^{'} = \sum_{j=1}^{M} \delta_{ij}$ indicates whether user i is chosen in any channel, and $R = \sum_{j=1}^{M} R_j$ may be seen as the bandwidth of the united channels. Then the Dantzig upper bound([18]) of the corresponding 0-1 Knapsack Problems may be used as the objective profit. Assume all users have been reordered so that: $C_1 \ge C_2 \ge \cdots \ge C_K$. Let k be given by $k = \min\{j : \sum_{i=1}^{j} B_i \ge R\}$. Then the upper bound of the objective profit is given by:

$$U_{profit} = \sum_{i=1}^{k-1} B_i C_i + (R - \sum_{i=1}^{k-1} B_i) C_k. \tag{7}$$

C. Profit Oriented Bandwidth Allocation Method for Real-time Large Scale Multichannel Bandwidth Allocation

The basic idea of the Profit Oriented Bandwidth Allocation Method (POBAM) contains two parts: first, considering the remaining available bandwidth of all channels and the remaining users that have not yet been given the bandwidth, pick out those that will be considered for bandwidth allocation at current iteration stage; then allocate the available bandwidth among the selected users. These two parts will be carried out repeatedly until either all users have received the requested bandwidth or the terminating condition is satisfied:

$$\min_{i=1,\ldots,K^{(k)}} B_i > \max_{j=1,\ldots,M^{(k)}} R_j, \tag{8}$$

where $K^{(k)}$ and $M^{(k)}$ are the numbers of remaining users and channels for the bandwidth allocation at stage k. This condition means that no channel can provide any users requested bandwidth any more. In the following, the two main parts of POBAM will be given detailed description in III-C.1) and III-C.2) respectively, and the complete POBAM is shown in III-C.3).

1) User Selection Based on Dynamic Programming: At stage k, $M^{(k)}$ channels are available for further bandwidth allocation, and $R_i^{(k)}$ is available in channel j ($j = 1,\cdots,M^{(k)}$). The united channels' bandwidth is $R^{(k)} = \sum_{j=1}^{M^{(k)}} R_j^{(k)}$. Besides, $K^{(k)}$ users wait for the bandwidth allocation with request $B_i^{(k)}$ and unit bandwidth cost $C_i^{(k)}$, where $i = 1,\cdots,K^{(k)}$. Define $P_i^{(k)}(r)$ as the value of the optimal solution for problem (6) when only the first i users among the $K^{(k)}$ users are requesting for a portion of the r bandwidth. Then it is easy to see that the principle of optimality in dynamic programming holds for the surrogate allocation problem (6), i.e.

$$P_i^{(k)}(r) = \max\{P_{i-1}^{(k)}(r), P_{i-1}^{(k)}(r - B_i^{(k)}) + C_i^{(k)} B_i^{(k)}\} \tag{9}$$

which can be rewritten in the following forms:

$$\begin{cases} P_0^{(k)}(r) = \begin{cases} 0 & r \ge 0 \\ -\infty & r < 0 \end{cases} \\ P_i^{(k)}(r) = \max\{P_{i-1}^{(k)}(r), P_{i-1}^{(k)}(r - B_i^{(k)}) + C_i^{(k)} B_i^{(k)}\} \end{cases} \tag{10}$$

for $i = 1,\cdots,K^{(k)}$, and $0 \le r \le R^{(k)}$. The surrogate problem will then be solved by generating $P_1, P_2, \ldots, P_m$ successively. Hence, based on dynamic programming([19]), the method for selecting users is presented as **Algorithm 1**: USERSELECTIONDP.

Clearly, algorithm USERSELECTIONDP has time complexity $O(K^{(k)}R^{(k)}/rStep)$, which may be adjusted by the bandwidth searching step $rStep$. The suggested value of $rStep$ is the minimum bandwidth requested among all users. Smaller values for $rStep$ can be used for better performances and larger values can be used to reduce the time complexity with corresponding compromised performance.

Algorithm 1: USERSELECTIONDP(B,C,tr,rStep)
Input:*users' bandwidth request vector* $\mathbf{B}$ *and Unit bandwidth cost vector* $\mathbf{C}$,*total bandwidth* $\mathbf{tr}$,
and bandwidth searching step $\mathbf{rStep}$;
Output:$\mathbf{SU}$,*selection of the users,1 selected,0 otherwise*

```
1. BS=⌊ tr/rStep ⌋; k ← size of B
2. for  i ← 0 to BS do P[0,i]← 0;
3.  for  i← 1 to k do
4.       { for  j← 0 to BS do {  r← j*rStep;
5.         if B[i]<r and B[i]*C[i]+P[i-1,⌊r-B[i]⌋] >P[i-1,j]
6.           then {P[i,j]← B[i]*C[i]+P[i-1,⌊ r-B[i]⌋];
7.      keep[i,j]← 1;}
8.         else{P[i,j]←P[i-1,j];keep[i,j]← 0;} } }
9.  j← BS; for i← K downto 1 do {SU[i]← keep[i,j];
10. j← ⌊(j*rStep-w[i])/rStep⌋; }
11.return SU;
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2) Bandwidth Allocation Among Selected Users: The bandwidth allocation is designed as Inheritor Survival Competition Allocation Method (ISCAM), and is profit maximization oriented. ISCAM treats each user as a generation, and different allocation policies as different family histories. Every generation consumes a certain resources(bandwidth) at some place(channel) with some cost(unit bandwidth cost*bandwidth). A constant living population size is kept with best effort. For each generation, every member is greedy and will try to have a child at every proper place, after which he will die and the children will compete with other families' children for survival to keep a constant population size. If someone finds no place with plenty resource for his child, he will keep alive and compete for the survival of the family. The survival principle is profit oriented and is based on the cumulative cost for the family survival.

The selected users at current stage are reordered such that: $\overline{C}_1 \geq \overline{C}_2 \geq \cdots \geq \overline{C}_s$, where s is the number of selected users. This order is also the inherited order from parent to child, and ensures that user with higher cost will be considered first. $\overline{B}_i$ bandwidth is requested by user i. The allocation matrix is $\overline{\Delta}$, with M rows and s columns. The population size is N.

At the lth$(0 \leq l < s)$ generation, denote the fth$(1 \leq f \leq N)$ family as

$$\mathfrak{F}_f^{(l)} = \left(P_f^{(l)}, \mathbf{R}_f^{(l)}, \mathbf{H}_f^{(l)}\right) \in \mathbb{S}^{(l)} \tag{11}$$

where $P_f^{(l)}$ is the cumulative cost($P_f^{(l)} = 0$ when $l = 0$), $\mathbf{R}_f^{(l)}$ is a row vector with size M recording the remaining available bandwidth in every channel, and $\mathbf{H}_f^{(l)} = [H_f^{(l)}(1), \cdots, H_f^{(l)}(l)]$ is a vector with l length keeping the history of the family. $H_f^{(l)}(i)(i = 1, \cdots, l)$ records the channel in which the ith generation of the family got the requested bandwidth, and $H_f^{(l)}(j) = 0(1 \leq j \leq l)$ means that the jth generation of the family was temporarily interrupted for lack of bandwidth in any channels. Then the places where the $l+1$th generation of family f could get the requested bandwidth are

$$\mathbb{G}_f^{(l)} = \left\{ i \left| R_f^{(l)}(i) \geq \overline{B}_{l+1}, i = 1, \cdots, M \right. \right\}, \tag{12}$$

in each of which a new family will be formed to compete for survival with cumulative cost $P'^{(l)}_f = P_f^{(l)} + \overline{C}_{l+1}^{(k)} \overline{B}_{l+1}^{(k)}$. For each new family, the family history will add where the $l+1$th generation member gets the bandwidth: $\mathbf{H}'^{(l)}_f = [\mathbf{H}_f^{(l)}, i](i \in \mathbb{G}_f^{(l)})$. Denote vector $\sigma(i) = [0\ 0 \cdots 1 \cdots 0]$, in which the ith element is 1. Then the remaining resources of the child family is $\mathbf{R}'^{(l)}_f = \mathbf{R}_f^{(l)} - \sigma(i)\overline{B}_{l+1}(i \in \mathbb{G}_f^{(l)})$. If $\mathbb{G}_f^{(l)}$ is an empty set, the present family will keep alive and try to compete for survival with $P'^{(l)}_f = P_f^{(l)}$,$\mathbf{H}'^{(l)}_f = [\mathbf{H}_f^{(l)}, 0]$and $\mathbf{R}'^{(l)}_f = \mathbf{R}_f^{(l)}$. Define

$$\Phi(\mathbb{G}_f^{(l)}) = \begin{cases} 0, & \mathbb{G}_f^{(l)} \in \emptyset \\ 1, & otherwise \end{cases}, \tag{13}$$

The child family set of family f at the lth generation will be

$$\begin{aligned} \mathbb{S}'^{(l)}_f = \Big\{ & \left(P'^{(l)}_f, \mathbf{R}'^{(l)}_f, \mathbf{H}'^{(l)}_f\right) \Big| \\ & P'^{(l)}_f = P_f^{(l)} + \overline{C}_{l+1}^{(k)} \overline{B}_{l+1}^{(k)} \Phi(\mathbb{G}_f^{(l)}), \\ & \mathbf{H}'^{(l)}_f = [\mathbf{H}_f^{(l)}, i], \mathbf{R}'^{(l)}_f = \mathbf{R}_f^{(l)} - \sigma(i)\overline{B}_{l+1}, \\ & where i \in \mathbb{G}_f^{(l)}, i = 0 \ when \ \mathbb{G}_f^{(l)} \in \emptyset \Big\} \end{aligned} \tag{14}$$

Then the candidate family of the $(l+1)$th generation are

$$\mathbb{S}'^{(l)} = \bigcup_{f=1,\cdots,N} \mathbb{S}'^{(l)}_f \tag{15}$$

which is the union of all child families of the lth generation families. The size of set $\mathbb{S}^{(l)}$ may be far larger than the population size N, and N families in $\mathbb{S}^{(l)}$ should be selected.

A certain survival principle need to be established for the selection. In order to serve our profit maximum objective, families with higher cumulative cost will be picked with priority, and those with equal cost will be selected randomly with equal probability. Divide $\mathbb{S}^{(l)}$ into u subsets:

$$\mathbb{S}'^{(l)} = \mathbb{S}'_1 \bigcup \mathbb{S}'_2 \bigcup \cdots \bigcup \mathbb{S}'_u, \tag{16}$$

which satisfies $\forall i, j, 1 \leq i < j \leq u, \forall \mathfrak{F}_1 \in \mathbb{S}'_i, \forall \mathfrak{F}_2 \in \mathbb{S}'_j$, cumulative cost of family $\mathfrak{F}_1$ is bigger than that of $\mathfrak{F}_2$. The selected $(l+1)$th generation families will be

$$\mathbb{S}^{(l+1)} = (\mathbb{S}'_1 \bigcup \mathbb{S}'_2 \bigcup \cdots \bigcup \mathbb{S}'_{t-1}) \bigcup \overline{\mathbb{S}}'_t, \tag{17}$$

in which

$$\left| \mathbb{S}'_1 \bigcup \cdots \bigcup \mathbb{S}'_{t-1} \right| < N \leq \left| \mathbb{S}'_1 \bigcup \cdots \bigcup \mathbb{S}'_t \right|, \tag{18}$$

and $\overline{\mathbb{S}}'_t$ is a subset of $\mathbb{S}'_t$ randomly chosen so that $\left|\overline{\mathbb{S}}'_t\right| = N - \left|\mathbb{S}'_1 \bigcup \cdots \bigcup \mathbb{S}'_{t-1}\right|$. Here, $|\bullet|$ denotes the size of set $\bullet$.

The $l+1$th generation families will go on propagating. The procreation and survival process will continue until all remaining resources(bandwidth) have been used up or the last generation(sth) families are born. The final allocation scheme is the history of the family with the most cumulative cost:

$$\overline{\delta}_{ij} = \begin{cases} 1, & i = H_m^{(s)}(j) \\ 0, & otherwise \end{cases} \quad i = 1, \cdots, M; j = 1, \cdots, s \quad (19)$$

where $\mathbf{H}_m^{(s)} = [H_m^{(s)}(1), \cdots, H_m^{(s)}(s)]$ belongs to family $\mathfrak{F}_m^{(s)}$, and $\forall \mathfrak{F}^{(s)} \in \mathbb{S}^{(s)}$, $P_m^{(s)}$ of $\mathfrak{F}_m^{(s)}$ is no smaller than $P^{(s)}$ of $\mathfrak{F}^{(s)}$.

Algorithm ISCAM is shown in **Algorithm 2** with time complexity $O(sN)$ which can be adjusted by population size N.

Algorithm 2: ISCAM(B,C,R,N)
Input*:selected users' bandwidth request vector* $\mathbf{B}$ *and unit bandwidth cost vector* $\mathbf{C}$*, channel bandwidth vector* $\mathbf{R}$*,population size* $\mathbf{N}$
Output*:allocation matrix* Δ.
1.**Reorder** users so that $\overline{C}_1 \geq \overline{C}_2 \geq \cdots \geq \overline{C}_s$ with
2. corresponding $\overline{B}_1, \overline{B}_1, \cdots, \overline{B}_s$, s is size of B;
3.**Initialize**: $\mathbb{S}^{(0)} = \{(P_f^{(0)} = 0, \mathbf{R}_f^{(0)} = R, \mathbf{H}_f^{(0)} = \emptyset) | f = 1, \cdots, N\}$
4.**for** l $\leftarrow$ 0 **to** s-1 **do** $\{$
5. **for** f$\leftarrow$ 1 **to** N **do** $\{$
6. **Family Form**: get $\mathbb{S}'^{(l)}_f$ according to (14)$\}$
7. **Family Survival**: get $\mathbb{S}^{(l+1)}$according to (17)$\}$
8.**Allocation**:pick the best family and allocate
9.the bandwidth according to(19)
10.**Restore** the allocation result $\overline{\Delta}$ to original user order Δ, and **Return** Δ;

Algorithm 3: POBAM(B,C,R)
Input*: users' bandwidth request vector* $\mathbf{B}$, *unit bandwidth cost vector* $\mathbf{C}$*, channel bandwidth* $\mathbf{R}$
Output*:allocation matrix* Δ.
1.**Initialize**:$rStep, N$, $\Delta \leftarrow \{\mathbf{0}\}$. Remove users/channels
2. that violate (3)/(4) and get B',C',R';
3.**while** B' is not empty **and** R' is not empty **do**$\{$
4. tr $\leftarrow$ sum of all R' elements;
5. SU $\leftarrow$**USERSELECTIONDP**(B',C',tr,rStep);
6. select the users according to SU, and get $\overline{B'}, \overline{C'}$;
7. $\Delta' \leftarrow$ **ISCAM**($\overline{B'}, \overline{C'}$,R',N);
8. **Record** the allocation in Δ according to Δ' and SU;
9. **Remove** the satisfied users and the allocated
10. bandwidth in each channel, then remove the
11. remaining users/channels that violate (3)/(4),
12. get B',C',R'; $\}$
13.**return** Δ;

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3) Profit Oriented Bandwidth Allocation: The complete Profit Oriented Bandwidth Allocation Method (POBAM) is shown in **Algorithm 3**. Clearly shown in **Algorithm 3**, the output of USERSELECTIONDP will be the input of **ISCAM**. Whether the allocation operations will be terminated or not is judged after the operations in step 6 of **Algorithm 3**, which uses Eq.(3) and (4) as the user and channel removing conditions. The iteration will stop when either no valid user (judged by Eq.(3)) or no valid channel (judged by Eq.(4)) exist. POBAM has time complexity $O(K \cdot r/rStep + KN)$, in which K is the number of users and r is the united channel bandwidth. Both the searching step $rStep$ and the population size N can be adjusted to get a balance between the performance and complexity. POBAM is near global optimal since the user selection operations in POBAM are based on dynamic programming, which itself has been proved to be global optimal([19]).

IV. Simulation Results and Performance Analysis

For mobile reception, we consider a robust DVB-T mode in the simulations: 16-QAM constellations, 2K mode COFDM modulator which employs 1075 subcarriers with guard interval $1/4(56\mu s)$, and $r = 1/2$ code rate (data rate 9.95Mbps) in a 7.61MHz UHF channel. One MPEG-2 transport stream is transported for each DTV program, and each stream takes about 4-6Mbps for standard definition television([20]). Due to the compression of the original videos and the traffic smoothing techniques used in the MPEG-2 encoder, the bandwidth for transmitting DTV programs varies slightly from time to time([21]). So the high quality digital television program is assumed to be a near CBR stream having Gaussian distributed data rate with mean 6Mbps and small variance 100Kbps. Hence each air channel contains one DTV program. The hybrid DVB-T access architecture is especially suitable for unidirectional IP data services which require high downlink data rate, and we assume that all user requests are IP content downloading. Besides, for each user, the access requests come as poisson arrival processes with gaussian distributed data rate requirement. The service time after each successful access is exponentially distributed. Users are classified into five priorities, and the one with priority $P = i$ is assumed to pay i for unit bandwidth.

Consider the joint exploitation of five air channels, and each contains one high quality DTV program. Thirty active users with different priorities(uniformly distributed) are applying for broadband access services with random data rate request which has mean value 768Kbps and variance 200Kbps. The mean service time of all users is configured as $1/\mu = 10s$. Fig.2 presents the simulation results in the form of vertical column graph for comparing the joint channel scheduling and separate channel scheduling. POBAM is used as the joint channel bandwidth management policy. The system profit has been traced for the first 30 allocating time slots. At each time slot, three columns, marked by blank, slash and grid rectangles respectively, are plotted, giving the system profit earned through separate channel allocation, joint channel allocation and the ideal channel allocation(profit upperbound) correspondingly. As we can see from the graph, the joint channel resource management will effectively improve the utilization value of DVB-T channels as compared with separate channel management. Averagely, POBAM performs 30.9% better than separate channel scheduling under our simulation scenarios.

Then we compared the performance of using POBAM and genetic method([15]) to allocate the available joint channel bandwidth. In genetic method, a maximum of 500 generations is configured, and the terminating condition is that the variance of the last 50 fitness value is no larger than 0.1. Fig.3 shows the simulation results, which traces the system profit earned through the bandwidth allocation for the first 100 allocating time slots. The system profit of both POBAM and genetic method has been normalized by the profit upperbound given by (7). As shown in Fig.3, POBAM outperforms genetic method greatly. On average, POBAM reaches 93.6% of the profit upperbound, while the genetic method only 82.1%. Besides, during this simulation, the average execution time of POBAM is only $0.0074/11.52 = 0.06\%$ of the genetic method. Hence, POBAM is quite competent for on-line joint channel bandwidth allocation.

With POBAM, users with different priorities will receive services with different QoS, which is measured by the successful access rate. Fig.4 gives the simulation result about the QoS ability of POBAM. Five air channels are also used as the carriers of additional IP data services. The priority of each user is randomly selected between 1 and 5. We've given simulations over different active user numbers, ranging between 10 and 60, and the probability that the user will succeed in getting the access admission is presented. As shown in Fig.4, when the system has light load(10 to 20 active users), most users will get a portion of the access bandwidth. With the increase of active users, those with lower priorities will be rejected for access to give more room for users with higher priorities. The users with the highest priority($P = 5$) have always been admitted to access the Internet for this load range. It is proved by the simulation result that POBAM can provide effective QoS differentiation.

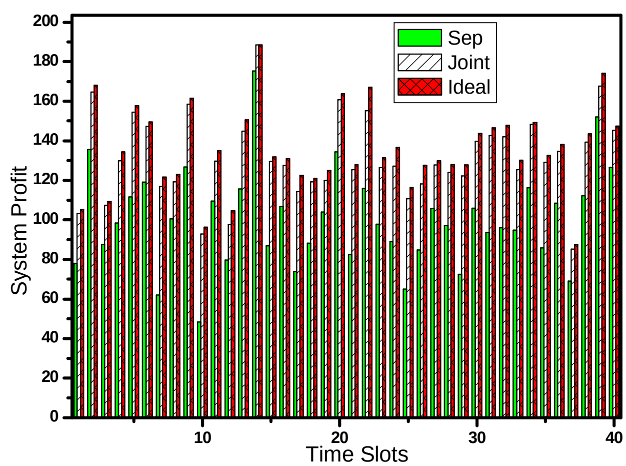

Fig. 2. System Profit Comparison between Joint and Separate Channel Management

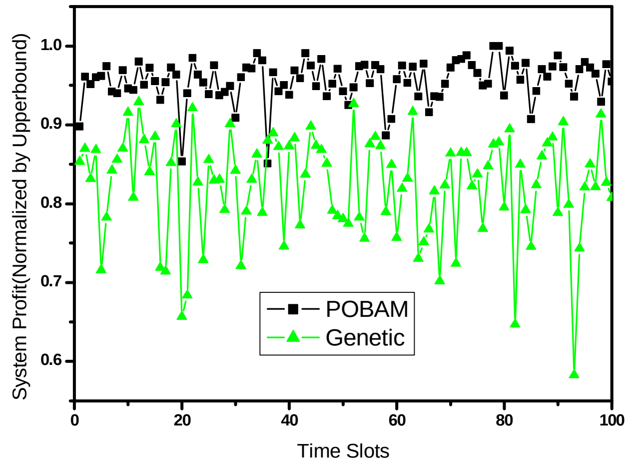

Fig. 3. System Profit Comparison between POBAM and Genetic Method (normalized by upperbound of system profit)

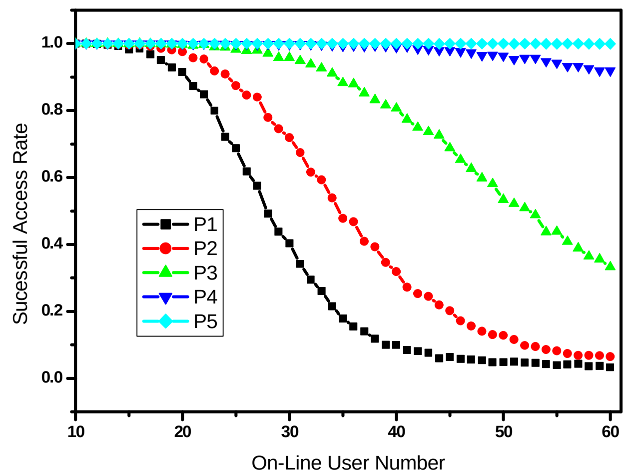

Fig. 4. QoS(access rate) Differentiation Provided by POBAM

V. Conclusions and Future Work

In this paper, a multichannel architecture of integrated communication and broadcast networks has been proposed with an instance of the integrated Internet and DVB-T network. The main advantage of the multichannel architecture is that it can provide huge access bandwidth compared with other access technologies, especially if the user terminal supports multi-channel signal receiving and all broadcast channels are exploited for additional IP data transmissions. The integration of Internet and DVB-T network has salient advantages as compared with other wireless access systems. The robust transmission capability of DVB-T will enable high data rate transmissions to users with high mobility. Besides, the wireless access bandwidth is very huge compared with other wireless access systems. Hence it can be a highly recommendable candidate of future 4G/5G communications for providing broadband wireless access services to users with high mobility.

The bandwidth management in the multichannel architecture of ICBN is different with traditional existing bandwidth management policies. In order to give effective management of the multichannel resources, POBAM is presented. The simulation results of POBAM powerfully show that POBAM can effectively exploit the broadcast multichannel resources for profit near global maximization, and the joint channel management outperforms the separate channel management greatly. POBAM can also supply services with effective QoS differentiation according to their QoS levels. The complexity of POBAM is low enough for on-line multichannel bandwidth management even when there are dozens of joint channels and hundreds of active users.

This paper has presented a sketchy multichannel architecture, and further studies are still needed to incorporate more aspects for such a convergence, since both the network paradigms and working principles are quite different. For example, though the feedback channels are available by using some other access systems, it may be heavily delayed. As a result, the ACK/NACK packets may be delayed too, resulting in bursty feedbacks of ACK/NACK's. Hence it is quite necessary to analyze the characteristics of the return channel and its influence on the downlink traffic, and to modify TCP/IP to adapt this asymmetry communication.

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