Architectures and Handoff Schemes for CATV-Based Personal Communications Network*

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Abstract *The initial cost to provide personal communications services (PCS) based on the conventional networks is relative high. As the radio cells move toward smaller size, the traditional procedures for call setup and control are not suitable well due to the high handoff frequency. The cable TV (CATV) network is one of the most attractive backbones for PCS due to its prevalent and broadcast nature. This significantly reduces the implementation costs and the handoff overheads. This paper proposes two architectures for the CATV-based PCS system. In the first architecture, each base station is equipped with multiple fixed receivers to provide fast and seamless handoffs for mobile terminals. Nevertheless, it suffers from the expensive hardware cost. In the second architecture, each base station is only equipped with one tunable receiver. This simple and economic architecture suffers from the possibility of offset conflict when mobile terminals handoff between the cells. Three channel allocation algorithms are proposed to resolve the offset conflict problem. Simulation results indicate the one with the concept of clustering performs much better than the other two schemes in terms of offset conflict probability.*

1. Introduction

The Personal Communications Service (PCS) is becoming a reality because of the efforts of industries, governments, and standard organizations. The hardware architecture of a generic PCS system shown in Figure 1 is mainly composed by two equipments: the base stations and the backbone network. The major function of the base station is to communicate with the mobile terminals within its radio transmission range (or cell). To support user mobility, the base station is responsible to keep track of the presence of mobile terminals in its cell. The backbone network is conventionally based on the existing Public Switched Telephone Network (PSTN). When a mobile terminal moves to a new cell, the backbone network is responsible for finding or rerouting the path from the mobile terminal to whom it communicates with.

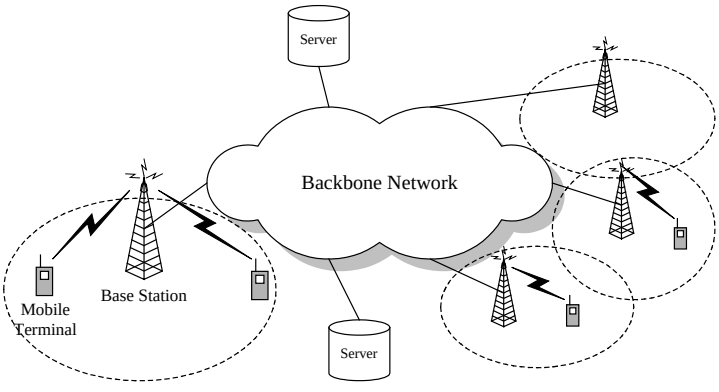

Figure 1. Hardware Architecture of the PCS system.

The PCS system, although has been proposed and implemented for years, still encounters some economical and technical problems. Conventional approach to implement a PCS system requires high initial costs for real-estate, equipment and wiring. These initial costs do not scale with the number of subscribers. Given these high initial costs and expected low monthly subscriber fees, it is not easy to make a profitable business case for PCS. In order to support mobility, sophisticated signaling procedures and complex hardware architectures are required. Worst of all, as PCS moves toward smaller sized cells in order to accommodate more users or to provide higher capacity, the conventional procedures for call setup and control would fail due to the frequency of the handoffs[2].

Different backbone network architectures have been proposed in recent years in order to make PCS more profitable and practical [2],[3],[7]. Among these architectures, the CATV network is considered the most ideal one for several reasons. First, the CATV networks have already been existed for years and they are more prevalent than the others are. Second, the cost of the CATV-based PCS system is lower[6]. Third, the handoff procedures are simpler since the CATV is a broadcast network.

This paper proposes two architectures for the CATV-based PCS system. In the first architecture, each base station is equipped with multiple fixed receivers, one for each downstream channel, so that several downstream channels can be received simultaneously. This architecture furnishes seamless and fast handoff procedure, but suffers from the expensive hardware cost. In the second architecture, each base station is equipped with a tunable receiver. This tunable receiver has the capability to access the full range of downstream channels but only one of them can be retrieved at a time. Based on this architecture, we can have a fast handoff procedure for roaming terminals. Nevertheless, it is also possible to introduce *the offset conflict problem* as handoff occurs. Three *offset assignment algorithms* are also proposed to keep the offset conflict rate as low as possible. Simulation results show that the one with the concept of clustering performs much better than the other two algorithms in terms of offset conflict probability.

The rest of this paper is organized as follows. The advantages of the CATV-based PCS system are addressed in Section 2. Two architecture designs for CATV-based PCS system are introduced in Section 3. The offset conflict problem and the proposed offset allocation algorithms are presented in

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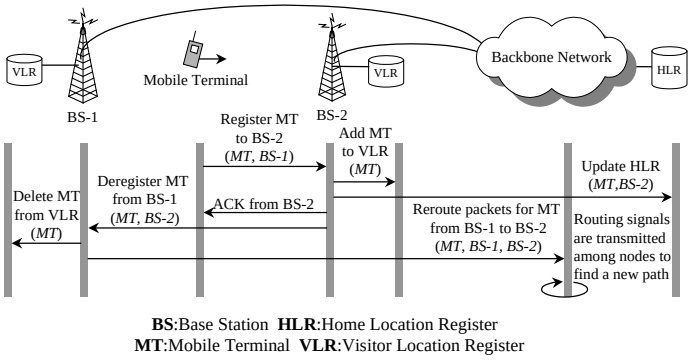


Figure 2. Typical handoff procedures in PCS system.

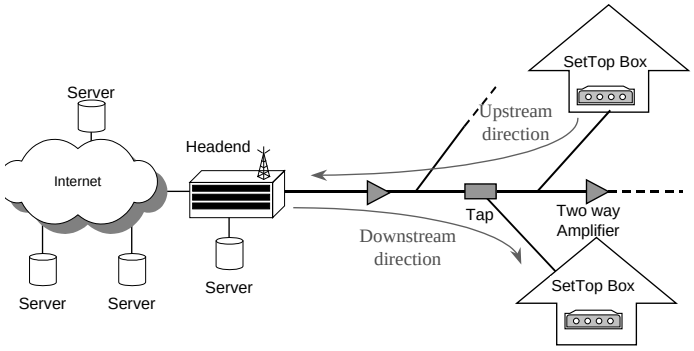


Figure 3. Architecture of the CATV network.

Section 4. The simulation model and results are reported in Section 5. Some conclusion remarks are given in Section 6.

2. CATV-Based PCS

Traditional handoff procedures in PCS system[5] are shown in Figure 2. When a mobile terminal handoffs from base station BS-1 to base station BS-2, the required signals and messages are illustrated. We can see that the handoff procedures are complicate. Note when BS-1 notifies the backbone network to reroute the packets of the mobile terminal, many signals are also required among the nodes in the backbone network. This is the most challenge and critical part in designing a PCS system. Moreover, as the PCS system moves toward smaller sized cells in order to accommodate more users or to provide higher capacity for multimedia applications, the handoff happens more frequently. This also increases the blocking probability for call setup.

A mechanism called *Virtual Connection Tree* (VCT) has been proposed to reduce the handoff signals in ATM-based wireless network[2]. A virtual connection tree is a collection of base stations and wired ATM switches and links. The root of the tree is an ATM switch of the wired network and the leaves of the tree are base stations. For each mobile connection, the VCT provides a set of *Virtual Connection Numbers* (VCNs), each associated with a path from the root to one leaf. When a mobile terminal wishes to handoff to another base station in the same VCT, it transmits ATM cells with the VCN assigned for use between itself and the new base station. As the root receives the first cell with different VCN from a given mobile connection, it interprets this as a handoff and updates its routing table for that connection. Consequently, cells, with the new VCN associated with the path from the root to the new base station, can be properly delivered from the root to that mobile terminal. The VCT mechanism eliminates the rerouting signals for handoff within the range of a VCT in ATM-based PCS system with the cost of maintaining a big VCN table in each ATM switch. When mobile terminal moves out the range of a VCT, the traditional rerouting signals are still required for inter-VCT handoff in ATM backbone network.

The CATV network, as shown in Figure 3, is an asymmetric, broadband network and is now under the standardization process in the IEEE 802.14 project[4]. For a connection in the CATV network, sender transmits packets to the *headend* through an *upstream channel*, and then the headend broadcasts these packets to one or several of the *downstream channels*. Handoff procedures can be significantly simplified within a metropolitan area if the CATV network is employed as the PCS backbone network. The concepts of CATV-based PCS system have been proposed by several research labs and cable companies[3],[7]. CATV network is a shared, broadcast media. That is, packets for a user are actually broadcast to all nodes in the network. This broadcast nature furnishes the opportunity to design fast and simple handoff procedures. Consider the case when a mobile terminal wishes to handoff in a CATV-based PCS system. It is unnecessary for the network to reroute the packets since they are broadcast to all base stations. As the rerouting signals are eliminated, the handoff procedures are greatly simplified.

The CATV network is suitable for PCS backbone network for more reasons. As the handoff procedures are simplified, the hardware design of the base stations and the mobile terminals becomes easier. Accordingly, the cost and the size of the equipment can also be reduced. The CATV network has been existed for years and its service area keeps growing. Seamless indoor/outdoor services would be easier to implement since cable drops span to the homes. Cable is a broadband (up to 1GHz) and high-speed (Gbps) media, which is suitable for today's multimedia applications. With regard to all these merits, we believe that the CATV-based PCS system will become more and more popular in the near future.

The suggested frequency spectrum for PCS traffic, as illustrated in Figure 4, is from 750 MHz to 1GHz. To efficiently use these precious bandwidth, each downstream PCS channel is further partitioned into a sequence of downstream frames, each consists of *D* slots. One can also request more bandwidth on the downstream channels for multimedia applications, such as VOD and WWW internet access, by asking more slots in the downstream frame.

3. Architecture Design

In this section, we propose two architectures for CATV-

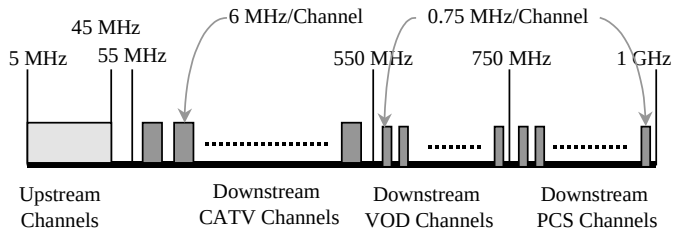


Figure 4. CATV frequency spectrum.

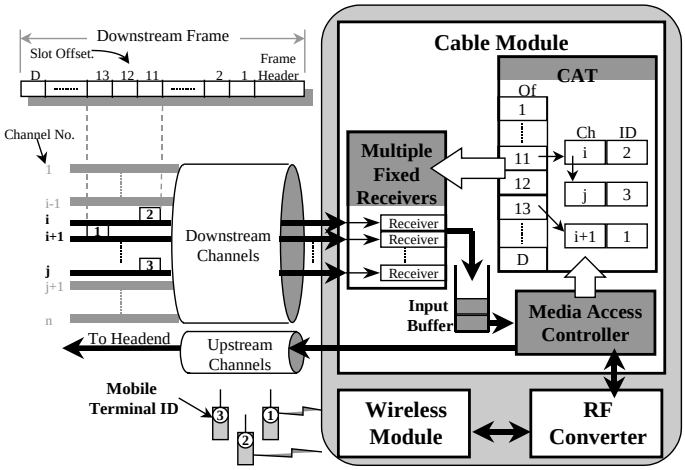


Figure 5. Architecture of the base station with multiple fixed receivers.

based PCS system to simplify the handoff procedures. Before describing the details, we first present the basic components of the base station in both architectures. The base station is composed by the following three modules: the *wireless module*, the *Radio Frequency* (RF) *converter*, and the *cable module*. The *wireless module* is responsible for communicating with mobile terminals within the cell of a base station. The Media Access Control (MAC) protocol of the radio links between the wireless module and mobile terminals can be, but not restrict to, the standard defined by IEEE 802.11[1]. The function of the *RF converter* is to interchange the signal format (such as: modulation, cell format, and frequency spectrum) between the wireless RF signals and the cable RF signals. If the modulation algorithms and the slot formats are the same in both wireless and cable modules, the RF converter can simply be a frequency converter. The *cable module* is in charge of transmitting data to and receiving data from the headend. This module plays an important role in handoff because it is the communication interface between base stations. Hence, we will focus on the design of the cable module and propose the following two architectures.

3.1 Base station with multiple fixed receivers

3.1.1 Architecture

In order to provide fast and seamless handoffs for mobile terminals in a CATV-based PCS network, architecture for the base station is proposed as shown in Figure 5. The cable module is equipped with *multiple fixed receivers*, a *channel allocation table* (*CAT*), a *media access controller* and an *input buffer*. Each receiver is responsible for receiving data in a fixed downstream channel. In this way, the base station is capable of receiving data from several downstream channels simultaneously and the offset conflict never happens. The set of downstream channels can be accessed by the multiple fixed receivers are denoted the *accessible channels*. The CAT of each base station keeps which slot(s) in the downstream channels are allocated for each of the serving mobile terminals. The *media access controller* performs the MAC protocol of the cable networks and interprets the control messages to and from the headend to maintain the CAT. For the case shown in Figure 5, each base station is equipped with k fixed receivers and the accessible channels are from

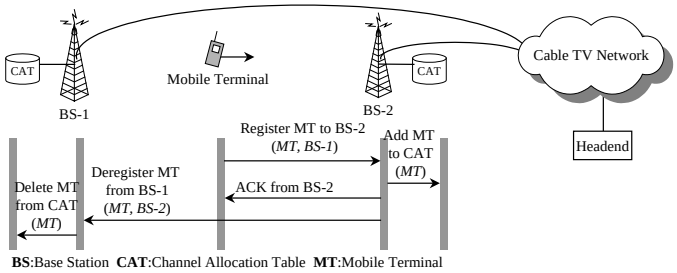


Figure 6. Handoff procedures in CATV-based PCS system; where each base station is equipped with multiple fixed receivers.

channel i to channel j; where $k = (j - i + 1)$. Note the offsets for mobile terminals MID 2 and MID 3 in the CAT are the same (offset = 11). These two slots will be received by the cable module simultaneously so an input buffer is needed to smooth the input rate and the output rate of the cable module. According to the CAT, each of the fixed receivers knows where and when to receive slots from the cable network.

3.1.2 Connection Setup Procedures

Consider the case when a mobile terminal wishes to establish a connection to a server in the CATV-based network. The mobile terminal first sends a connection request to the base station with its mobile ID, the network address of the server, and the QoS (Quality of Service) requirements. The wireless module of the base station first checks the status of the downstream radio channels. If no radio channel is available, the wireless module will reply a reject signal. Otherwise, the connection request will be forwarded to the cable module. When the cable module receives the call setup request, it forwards the request to the headend, and then to the destination (server). After the request was granted by the server, the headend calculates the number of slots requested by this connection (according to the QoS requirements) and reserves these slots on the accessible channels. If the available slots are not sufficient, the request is rejected. Otherwise, the channel number(s) and offsets of these reserved slots are sent to the base station. The base station updates its CAT accordingly and finally informs the assigned (*channel*, *offset*)s to the mobile terminal.

3.1.3 Handoff procedures

For illustration, the handoff procedures in this architecture are shown in Figure 6; where a mobile terminal in base station BS-1 handoffs to base station BS-2. The roaming terminal first issues a registration request to BS-2 with the mobile ID, the original base station (namely, BS-1), and the used (*channel*, *offset*)s. BS-2 puts these information into its CAT and notifies BS-1 to erase the entries of this mobile terminal. Finally, BS-2 issues a reply to the mobile terminal.

The most notable advantage of this architecture is the provision of seamless handoff environment. No extra handoff procedures are required in such a CATV-based PCS network. This greatly reduces the signaling traffic and decreases the blocking probability for call setup. Since the packets lost and QoS degradation problems caused by handoff are resolved in this architecture, the users can have better services when roaming around. Since only some of the downstream channels are employed in this architecture, the headend can therefore have a

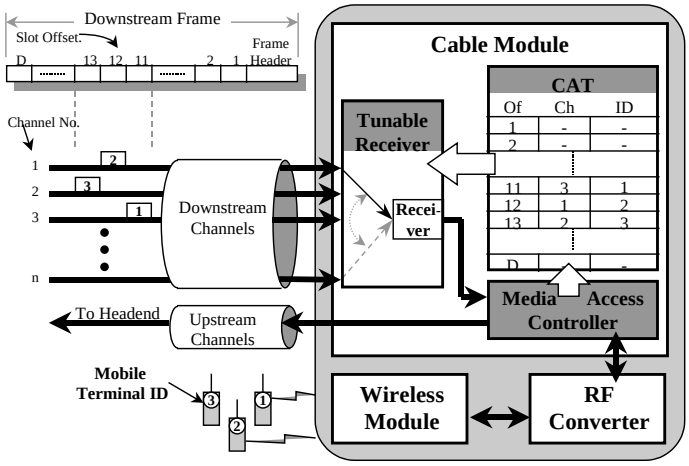


Figure 7. Architecture of the base station with a tunable receiver.

simpler network management task and bandwidth assignment protocol. However, the hardware complexity, physical size, and the cost of the base station are expensive. If the multiple fixed receivers can be designed into a single chipset, the size and cost can be greatly reduced and this architecture will be an ideal choice for today's PCS systems.

3.2 Base Station with a Tunable Receiver

3.2.1 Architecture

The second architecture for the cable module of a base station is shown in Figure 7. In this architecture, the cable module is composed by the *media access controller*, the *tunable receiver* and the *channel allocation table* (*CAT*). The *tunable receiver* is responsible for receiving downstream RF signals from the cable network. This tunable receiver can be tuned to any downstream channel, but only one channel at a time. The CAT of each base station keeps the assigned slot(s) in the downstream channels for each of the serving mobile terminals. The format of each entry in the CAT is (*Of, Ch, ID*), which means the slot at offset *Of* of the downstream channel *Ch* is assigned to the mobile terminal whose mobile ID (or network address) is *ID*. The tunable receiver can be properly tuned to a specified channel to receive data by looking up the CAT.

Note that, due to the tunable receiver can access only one channel at a time, the offset of each mobile terminal should be unique. Otherwise, only one mobile terminal can receive its packet at that slot time. This is called the *offset conflict problem* which happens when a mobile terminal moves into a cell from a neighboring cell and the assigned offset(s) identical to that of any existing terminal in the cell. In such case, more complicate handoff procedures are required to find new offset(s) for this mobile in the new base station.

3.2.2 Connection Setup Procedures

For the sake of comparison, the connection request example illustrated in the first architecture is employed here again. The call setup procedures from the mobile terminal to the wireless module are the same so we begin from the cable module. The cable module transmits the connection request and its channel allocation table (CAT) to the headend. The headend first forwards the connection request to the server. If the request is granted by the server, the headend will reserve bandwidth in the upstream (from server to headend) and the downstream (from headend to base station) channels for the connection. The amount of bandwidth, which is measured in number of slots, is calculated from the QoS requirements of the connection request. To prevent the offset conflict, the headend only reserves the slots whose offsets are different from those allocated in the CAT of the base station. If the headend is not able to find a sufficient set of offset conflict-free slots, the connection request will be rejected. Otherwise, the channel numbers and the offsets of these reserved slots are sent to the base station to update its CAT.

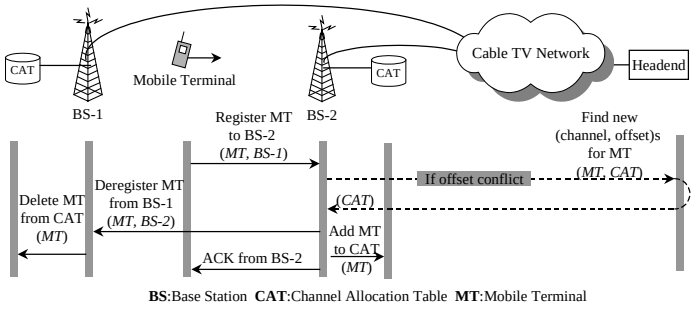


Figure 8. Handoff procedures in CATV-based PCS system; where each base station is equipped with one tunable receiver.

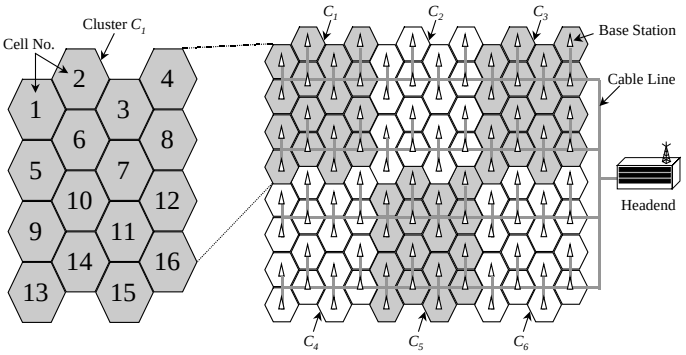
3.2.3 Handoff Procedures

The handoff procedures in this architecture are illustrated in Figure 8. Assume a mobile terminal handoffs from base station BS-1 to base station BS-2. The mobile terminal first sends BS-2 a registration request which consists of its mobile ID, the identifier of the original base station (namely, BS-1), and the associated (*channel*, *offset*)s. BS-2 checks the (*channel*, *offset*)s with its CAT. If offset conflict occurs, BS-2 asks the headend to find new slot(s) (offset conflict-free) for this mobile terminal. Then BS-2 puts the (*channel*, *offset*)s into its CAT and notifies BS-1 to erase the corresponding entries. Finally, BS-2 replies the new (*channel*, *offset*)s to the mobile terminal.

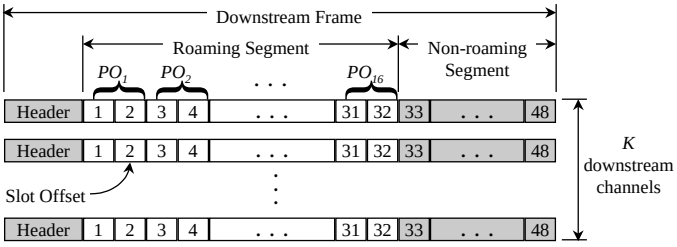
Note the headend may be unable to find proper (*channel*, *offset*)s for a mobile terminal if all the offsets have been occupied by the existing terminals within a base station. Consider the case when a mobile terminal in BS-1 moves to BS-2. Assume the downstream frame consists of 10 slots and the original offsets occupied by the roaming mobile terminal are 3, 9, and 10. Also assume the existing terminals in BS-2 have occupied the first eight slots of the downstream frame. Consequently, offset 3 of the roaming terminal conflicts with that of the existing terminals. In this case, the headend can not find a suitable offset for it due to all the offsets are occupied. Two actions may be taken by BS-2: either rejects the registration request or accepts the request with serving only two slots (the slot with offset 3 is not furnished). As a result, the mobile terminal may get connection interruption or QoS degradation (from 3 slots to 2 slots in a downstream frame).

4. Offset Assignment Algorithms

The goal of an offset assignment algorithm is to properly assign the slots for mobile terminals in order to keep the offset conflict probability as low as possible. When a mobile terminal makes a connection request or handoffs to a new base station with offset conflict, the headend should apply an offset



(a) A CATV network with six 4x4 clusters.



(b) Downstream frame structure (D = 48) and the preferred offsets of each cell.

Figure 9. Clustering concept for the PRO algorithm.

assignment algorithm to (re)assign the offsets for this mobile. The simplest algorithm is to randomly select from the unused offsets. We call this algorithm as *random* (*RND*) *algorithm*.

Note that the offset conflict problem happens only when a mobile terminal handoffs to one of its neighbor cells. If the offsets selected for the mobile terminal are not used by all its neighbors, the offset conflict won't happens when this mobile handoffs to any of its neighbor cells. The offset assignment algorithm based on this idea is called *Least Used by Neighbor* (*LUN*) *algorithm* and is described as follows. When a base station *BS* receives a connection request with *k* slots or detects an offset conflict with *k* offsets, it transmits the channel allocation table CAT_{BS} to the headend. The headend then asks all the neighbor cells of the *BS* to send back their channels allocations tables (denoted as CAT_{NBs}) and selects *k* least used offsets in CAT_{NBs} for *BS*. Of course, these *k* offsets should not be already occupied in BS. If more than *k* such offsets exist, the headend randomly picks *k* offsets of them. The LUN algorithm is more intelligent than the RND algorithm since the information from the neighbors are taken into account. However, more signals are required between the headend and the neighbor base stations to get these information. The time complexity is also increased since more channel allocation tables have to be examined.

Both these two algorithms are simple but the RND algorithm is not clever enough and the LUN algorithm suffers from overheads in handoff procedures. Following is a new offset allocation algorithm, called *Preferred Offsets* (*PRO*) *algorithm*, which provides a much better offset conflict probability without handling the CATs of the neighbor cells.

In the PRO algorithm, the offsets of a downstream frame are divided into two segments: the *roaming segment* and the *non-roaming segment*. The offsets in the roaming/non-roaming segment are intended to be assigned for roaming/non-roaming mobile terminals. We say that a mobile terminal is *non-roaming* if it never handoffs during a call. Otherwise, it is a *roaming* mobile terminal. Initially, when a mobile starts a connection request, it is recognized as a non-roaming mobile by the serving base station. The offsets for this mobile are first randomly selected from the unused offsets of the non-roaming segment. If these are insufficient, then the unused offsets in the roaming segment are randomly selected. When this mobile handoffs to a new base station and becomes a roaming mobile, it issues an *offsets reassignment request* to the new base station. This new base station will ask the headend to select new offsets for the mobile from the roaming segment. Roaming mobiles do not issue the offsets reassignment request again for the followed handoffs. The offsets of a roaming mobile remain unchanged until the offset conflict happens.

The concept of *preferred offsets* is introduced here. In our design, we suggest that all the cells should be divided into a set *C* of clusters, each consists of *m* cells. For example, Figure 9(a) shows that the 96 cells covered by a CATV network are divided into six clusters, each consists of 4x4 cells (m = 16). Cells in a cluster are labeled from 1 to *m* as that shown in Figure 9(a). Assume each downstream frame consists of *D* slots (offsets) and βD slots are allocated for roaming segment. Then each base station BS_i has a set PO_i of $\frac{\beta D}{m}$ preferred offsets. This means that when a roaming mobile terminal in BS_i issues an offset reassignment request or the offset conflict happens, the offsets in PO_i will be employed first. If all the offsets in PO_i are occupied, the free offsets in PO_j, $i \neq j$, are randomly selected. If all the offsets in the roaming segment are occupied, then the free offsets in the non-roaming segment are selected. For example, consider the example shown in Figure 9 again. Assume the CATV furnishes *K* downstream channels, each downstream frame consists of 48 slots (D = 48), and β = 2/3 as shown in Figure 9(b). Then we have PO_1={1,2}, PO_2={3,4},…, PO_{16}={31,32}. This means that for the cell *i* of each cluster, the preferred offsets are 2*i*-1 and 2*i*. Note that only the offsets are concerned by the base station, which of the *K* downstream channels is employed is not important.

The basic idea is that if all the slots for the roaming mobile terminals are assigned with the preferred offsets, then the offset conflict happens only when two roaming mobile terminals with the same offset(s) from the same cell of different cluster roams into the same cell. For example, assume roaming mobile terminals X and Y are assigned with (Ch_i, Of_1) and (Ch_j, Of_1) in cell 3 of clusters C_1 and C_2, respectively. Both X and Y will not offset-conflict with each other unless they roam into the same cell. In such case, the tunable receiver of the base station is not possible to receive the two slots with the same offset, even they are carried in different channels. The headend will resolve this conflict by reassigning offsets. What we want to emphasize here is that based on the clustering scheme, the cells with the same preferred offsets are regular separated by several cells. However, it is also possible that the number of roaming mobile terminals within a cell is more than the number of preferred offsets of the cell. As we have mentioned before, in such case, the preferred offsets of other cells will be allocated. This also may introduce a

higher offset conflict probability while the roaming mobile terminals handoff frequently.

5. Analysis and Simulation

5.1 Analysis

In this sub-section, the *offset conflict probability* (OCP) produced by the PRO and RND algorithms are analyzed. The OCP is defined as the probability of causing offset conflict when a roaming mobile terminal handoffs to a neighbor cell. The terminology used in the analysis are defined as follows:

- C : the number serving cells of the CATV network.
- D : the number of slots in a downstream frame. In PRO algorithm, a downstream frame is partitioned into roaming segment and non-roaming segment and the number of slots in each segment is D_{RS} and D_{NRS}, respectively.
- N : the number of mobile terminals in the CATV network.
- γ : the percentage of the roaming mobile terminals. That is, $N\gamma$ mobile terminals are roaming while $N(1-\gamma)$ are non-roaming.
- ω : the number of slots required by a connection. For the sake of simplicity, only $\omega = 1$ is considered in the analysis.
- L : the total number of handoffs (or roaming length) experienced by a roaming mobile terminal.
- ρ_{PRO} : the OCP produced by the PRO algorithm.
- ρ_{RND} : the OCP produced by the RND algorithm.
- ρ_{LUN} : the OCP produced by the LUN algorithm.

The analysis of the RND algorithm is given as follows. First of all, consider the case when L = 1, i.e., every roaming mobile terminal handoffs only once during its active duration. The OCP of the RND algorithm can be stated as

$$\rho_{RND} = \frac{\overline{N}}{D}, \qquad (5.1)$$

where $\overline{N} = \frac{N}{C}$ stands for the average number of mobile terminals within a cell. This also stands for the average number of assigned offsets in the CAT of a base station since ω = 1.

Consider the case when L > 1. Since the number of handoffs experienced by a mobile terminal is greater than one, it is possible that a roaming mobile terminal may move into the same cell many times. In case the previously occupied offset is still free when the mobile terminal visits the cell again, it can still be used without offset conflict if it is identical to the one currently assigned for the mobile terminal. As a result, we have $\rho_{RND} \le \frac{\overline{N}}{D}$. Consider the case when L = 2. Assume a roaming mobile terminal M with assigned offset Of is within cell A. M first handoffs to one of A's neighbor cells, say cell B. The OCP for the first handoff, denoted as ρ_1, is

$$\rho_1 = \frac{\overline{N}}{D}. \qquad (5.2)$$

After t unit times, M handoffs again to one of B's neighbor cells. If offset conflict happened when M handoffs to cell B (the probability is ρ_1), then it must have a different offset and the OCP of the second handoff still equals to $\frac{\overline{N}}{D}$. Consider the case when M moves to one of its neighbor cells without offset conflict (the probability is $1-\rho_1$) and then moves again without backing to the original cell (the probability is $\frac{5}{6}$). Then the OCP of the second handoff will still be equal to $\frac{\overline{N}}{D}$. However, if M moves back to the original cell (the probability is $\frac{1}{6}$), the previously used offset Of may be still free or occupied by a mobile terminal (roaming or non-roaming) which is active during time interval t. Let $\delta(t)$ and $\eta(t)$ denote the arrival rate and handoff rate for non-roaming and roaming mobile terminals, respectively. Then, the probability that offset Of is occupied when M backs to cell A is

$$\rho_{Of} = \left(\frac{\delta(t)}{C} + 6\times\frac{1}{6}\cdot\frac{\eta(t)}{C}\right)\frac{\overline{N}}{D}. \qquad (5.3)$$

Finally, the OCP of the second handoff (ρ_2) can be stated as

$$\rho_2 = \rho_1\frac{\overline{N}}{D} + (1-\rho_1)\left(\frac{5}{6}\times\frac{\overline{N}}{D} + \frac{1}{6}\rho_{Of}\right). \qquad (5.4)$$

From Equations (5.2) and (5.4), the OCP of the RND algorithm when $L = 2$ can now be stated as

$$\rho_{RND} = \frac{\rho_1+\rho_2}{2} = \frac{\overline{N}}{D}\cdot\frac{1}{12}\left(11 + \frac{\delta(t)+\eta(t)}{C} + \frac{\overline{N}}{D}\cdot\left(1-\frac{\delta(t)+\eta(t)}{C}\right)\right). \qquad (5.5)$$

When $\frac{\delta(t)+\eta(t)}{C} = 1$, Equation (5.5) can be further reduced into Equation (5.1). This means that if the number of occupied offsets within each cell is stable (each time a mobile terminal roams out, there is another mobile terminal roams in from neighbor cell or a new non-roaming mobile terminal is active), the OCP will not be affected by the number of handoffs experienced by the mobile terminals. As a result, the number of occupied offsets of this cell remains constant so the OCP is independent to the parameter L.

The analysis for the cases when $L > 2$ of the RND algorithm are not considered here since they are much more complex than the case when L = 2 or L = 1. However, ρ_{RND} can be generalized as

$$\rho_{RND} = \frac{\overline{N}}{D}\cdot\varepsilon(L), \qquad (5.6)$$

where $\varepsilon(L)$ is the variation introduced by parameter L and $\varepsilon(L) = 1$ when L = 1.

In the PRO algorithm, the downstream frame is partitioned into roaming and non-roaming segments for roaming and non-roaming mobile terminals, respectively. Consider the case when L = 1, if the number of non-roaming mobile terminals in a cell is less than the number of slots in the non-roaming segment (i.e., $\overline{N}(1-\gamma) \le D_{NRS}$), the OCP of the PRO algorithm becomes

$$\rho_{PRO} = \frac{\overline{N} \cdot \gamma}{D_{RS}}. \quad (5.7)$$

However, if $\overline{N}(1-\gamma) > D_{NRS}$, some offsets in the roaming segment may be occupied by non-roaming mobile terminals and the OCP of the PRO algorithm can be stated as

$$\rho_{PRO} = \frac{\overline{N} \cdot \gamma + \overline{N} \cdot (1-\gamma) - D_{NRS}}{D_{RS}} = \frac{\overline{N} - D_{NRS}}{D_{RS}}. \quad (5.8)$$

The OCP of the PRO algorithm is also affected by parameter L and the reason is the same as we have mentioned in the RND algorithm. As a result, the OCP of the PRO algorithm can be generalized as:

$$\rho_{PRO} = \begin{cases} \frac{\overline{N} \cdot \gamma}{D_{RS}} \cdot \varepsilon(L) & \text{if } \overline{N}(1-\gamma) \le D_{NRS} \\ \frac{\overline{N} - D_{NRS}}{D_{RS}} \cdot \varepsilon(L) & \text{otherwise.} \end{cases} \quad (5.9)$$

5.2 Simulation

In order to evaluate the effectiveness of the proposed PRO algorithm, some simulation programs were implemented. The OCP produced by the PRO algorithm is compared to those of the RND and LUN algorithms. The assumptions for the simulation are as follows (terminology are the same as in sub-section 5.1):

- C = 20x20 = 400 cells, which are partitioned into 25 4x4 clusters.
- D = 48, D_{RS} = 32 and D_{NRS} = 16.
- N is ranged from 500 to 10,000 in a step of 500. These mobile terminals are uniformly distributed over C cells.
- γ is considered from 10% to 90%, in a step of 20%.
- The number of downstream PCS channels K = 300.
- A roaming mobile terminal handoffs to one of its randomly selected neighboring cells.
- Simulation stops when the total number of handoffs reaches 1,000,000.

In the first simulation, the analytical OCPs of the RND algorithm (i.e., Equation (5.6)) and the PRO algorithm (i.e., Equation (5.9)) are compared with simulated OCPs when ω = 1 and L = 1. The results are shown in Figure 10, where we can see that for both RND and PRO algorithms, the analytical and simulated OCPs are very close to each other. This means that the analysis is significant.

Note that the curve of the PRO algorithm in Figure 10(a) is folded when $N = 7000$. This is because when $N \le 7000$, $\frac{N}{C}.(1-\gamma) = \frac{7000}{20 \times 20}(1-0.1) \le 16 = D_{NRS}$. Therefore, Equation (5.6) is reduced to Equation (5.4). When $N \ge 7500$, ρ_{PRO} is dominated by Equation (5.5) so the curve becomes steeper. This phenomenon is also applied to the curves of the PRO algorithm in Figure 10(b) and Figure 10(c). The simulation results also show that ρ_{PRO} is much less than ρ_{RND} when γ < 0.7. However, when γ ≥ 0.7, $\rho_{PRO} > \rho_{RND}$. This can be induced from Equations (5.1) and (5.7) as follows:

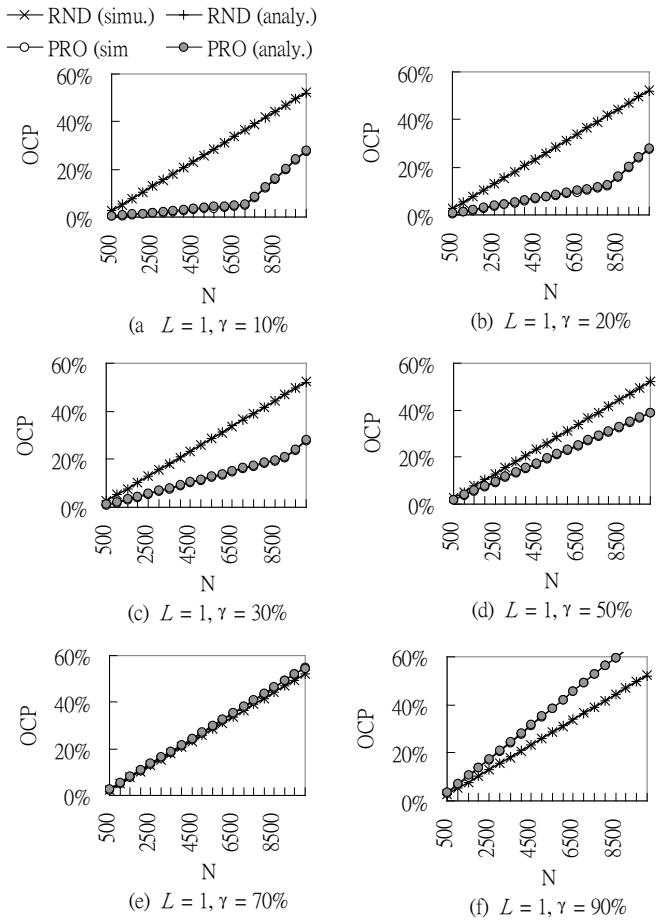


Figure 10. The analytical and simulated OCPs of the RND and PRO algorithms with ω = 1 and L = 1. (r = 10%, 20%, 30%, 50%, 70% and 90%)

$$\frac{\rho_{PRO}}{\rho_{RND}} = \frac{\frac{\overline{N} \cdot \gamma}{D_{RS}}}{\frac{\overline{N}}{D}} = \frac{D \cdot \gamma}{D_{RS}} \ge \frac{48 \times 0.7}{32} > 1 \Rightarrow \rho_{PRO} > \rho_{RND}.$$

It seems the OCP of the PRO algorithm becomes greater than that of the RND algorithm when $\gamma \ge 0.7$. Fortunately, in real world, γ is rarely more than 30%.

Figure 10 also illustrates the influence of roaming factor γ on the OCP. For the RND algorithm, the OCP is not influenced by γ due to the concept of roaming/non-roaming segment is not applied. For the PRO algorithm, larger γ produces higher OCP. This matches with the analysis in Equations (5.1) through (5.9).

Figure 11 shows how OCP is affected by the value of L for the RND and the PRO algorithms. From the simulation results we can see that the OCP becomes slightly lower as the value of L becomes larger. This phenomenon is reasonable because a longer roaming length also introduces more chance to revisit a cell. Consequently, by assuming $\varepsilon(L) = 1$, the ρ_{RND} in Equation (5.6) and the ρ_{PRO} in Equation (5.9) may be treated as the OCP upper bounds of the RND and PRO algorithms, respectively.

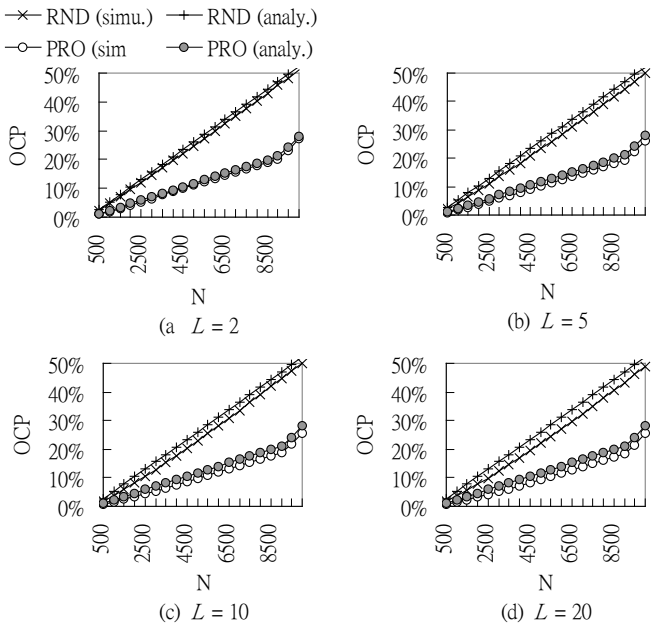


Figure 11. The analytical and simulated OCPs of the RND and PRO algorithms with ω = 1 and r = 30% (L = 2, 5, 10, and 20).

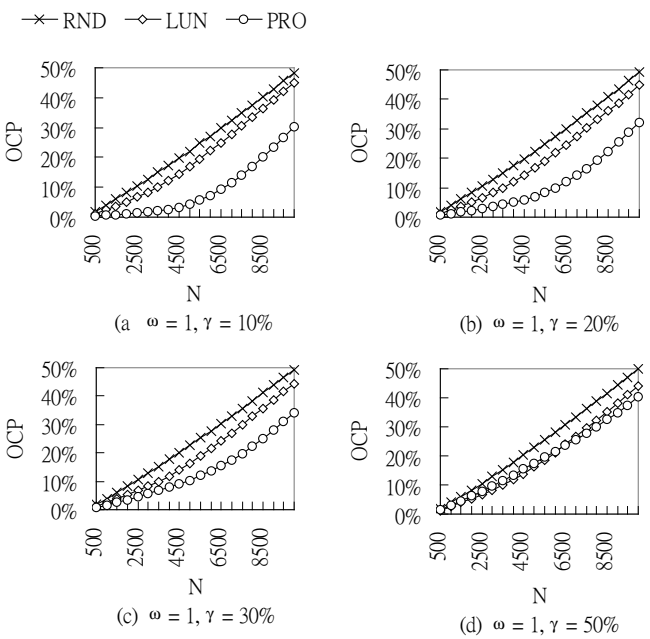


Figure 12. The OCPs produced by different offset assignment algorithms with $\bar{L} = 10$ and ω = 1 (r = 10%, 20%, 30%, and 50%).

Figure 12 shows the OCP produced by different offset assignment algorithms with ω = 1, and γ = 10%, 20%, 30% and 50%. The roaming length L is a normal distribution with a mean of 10. In realistic situation (i.e., $\gamma \leq 30\%$), the PRO algorithm performs much better than the other two algorithms, especially when the number of mobile terminals is small (i.e., in lightly loaded condition). Even when γ = 50%, the PRO algorithm still outperforms the RND algorithm and as good as the LUN algorithm. This is remarkable since the PRO algorithm needs as little information as the RND algorithm.

From the simulation results, we may conclude that the PRO algorithm furnishes the following advantages:

1. Only a few information are required to resolve the offset conflicts. As a result, the signaling traffic and computation overheads can be kept as few as possible.
2. Furnishes remarkable performance (keeps the OCP as low as possible) under lightly mobile situations ($\gamma \leq 30\%$).
3. Performs better than the LUN algorithm and RND algorithm even under highly mobile situations (γ = 50%).

6. Conclusion

The CATV network is an ideal backbone for PCS since it is a prevalent, broadcast media which reduces the initial costs and the handoff overheads. Two base station architectures for the CATV-based PCS system have been proposed in this paper. In the first architecture, each base station is equipped with multiple fixed receivers, one for each assigned downstream channel. Due to the broadcast nature of the CATV network, mobile terminals roaming among cells can have fast and seamless handoffs in this architecture. Nevertheless, the hardware cost for each base station is expensive. In the second architecture, each base station is equipped with only one tunable receiver to receive the slots from the downstream channels of the CATV network. This architecture is economical in hardware cost but also introduces the possibility of offset conflict when mobile terminals handoff among the cells. Three offset allocation algorithms (RND, LUN, and PRO) are proposed and compared. Simulation results show that the PRO algorithm performs much better than the other two algorithms in terms of offset conflict probability.

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