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PBX based mobility manager for wireless local loop

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SUMMARY

In a typical *wireless local loop* (WLL) system, a user can only access the wireless services at fixed locations. This paper proposes a *private branch exchange* (PBX) based mobility manager for WLL, which allows users to receive wireless service at any locations within the WLL service area. We show how the mobility manager can be implemented in a PBX environment where the base stations are connected to the PBX using standard line or trunk interfaces. The proposed mobility manager can be tailored to connect wireless system such as DECT or PACS. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: wireless local loop; PBX-based mobility manager

1. INTRODUCTION

Recently, many telecommunications operators have been looking for wireless technology to replace parts of the hard-wire infrastructure. The *wireless local loop* (WLL) technology [1] is considered as the most fitting solution as radio systems can be rapidly developed, easily extended, and are distance insensitive. Since a WLL eliminates the needs (such as wires, poles and ducts) essential for a wired network, it can significantly speed up the installation process.

A typical WLL system may consist of hundreds or thousands of base stations (BSs). In such a large-scale system, the mobility of a user may be limited to a small area. For example, if the customer premises equipment (CPE) is a fixed access unit, the user is only allowed to communicate with a specific BS. On the other hand, the user may wish to roam in the whole WLL service area. That is, one may want to connect the handset to any BS in the system. In such a case, the WLL must support mobility management to identify the 'locations' of users. Otherwise, thousands of the BSs would be asked to page a handset for call termination, which is technically infeasible. In this paper, we show how to modify a private branch exchange (PBX) to accommodate mobility management for a WLL. The features of our approach are listed below:

1. The PBX will serve as a WLL switch that connects *Public Switched Telephone Network* (PSTN) to the BSs.

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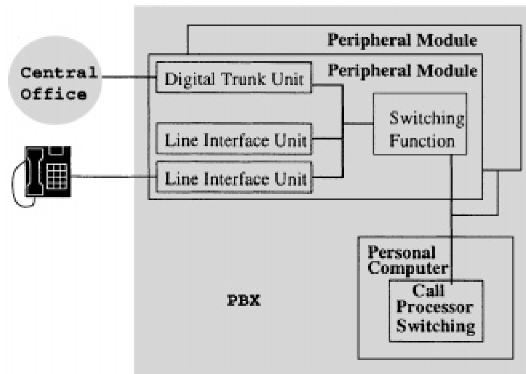

Figure 1. A simplified computer-controlled PBX architecture.

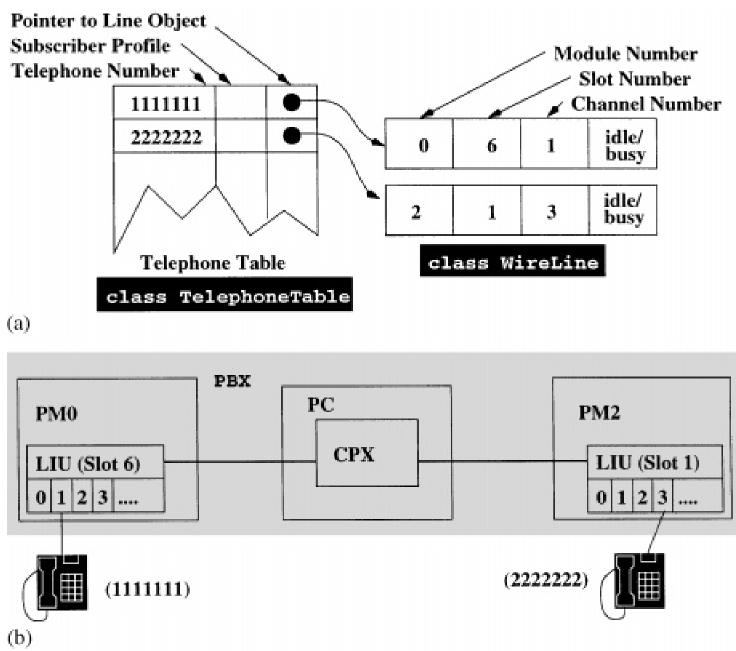

Figure 2. The telephone table and the corresponding physical configuration: (a) telephone table; (b) the corresponding physical configuration of (a).

2. The BSs are connected to the PBX through standard line or trunk interfaces. We use analog subscriber lines as an example for PBX-BS connections.
3. The line circuits in the PBX can connect to a wireline telephone or a wireless BS. The PBX automatically distinguishes the BS from the telephone. This feature allows flexible BS layout/installation.
4. A handset can communicate with any BS within the service area of the WLL.

2. A COMPUTER-CONTROLLED PBX ARCHITECTURE

Figure 1 illustrates a simplified computer-controlled PBX architecture. In this architecture a *Call Processor Switching* (CPX) unit connects to several *Peripheral Modules* (PMs). The CPX unit resides in a personal computer (PC), which receives and executes commands from the PC, and issues commands to control the PMs. The CPX also performs inter-PM switching functions (i.e. connecting two lines between different PMs). A PM consists of a switching function unit and several telephone interface unit cards. The switching function unit connects every incoming line to the destination outgoing line. The telephone interface unit cards provide various interfaces between the PBX and the outside world. For example, a PM many connect to telephone lines through the *Line Interface Unit* (LIU) or digital trunks through the *Digital Trunk Unit* (DTU). The LIU provides the interface between the PM and a telephone set. The DTU provides the interface between the PM and the trunks connected to the *Central Office* (CO) in the PSTN.

In a PM, every channel (telephone line) in a telephone interface unit card (*or slot*) is associated with a telephone number. Thus, in PC/CPX, a *telephone table* is required to map the telephone number to a channel. This table is used at the call control process layer to carry out the the call setup and release operations. Following the object-oriented approach, this table can be implemented by a class `Telephone Table` where every entry in the table consists of three fields (see Figure 2(a)): the telephone number, the subscriber profile (to indicate the offered services such as call forwarding, call waiting, and so on), and a pointer to a `WireLine` object. The `WireLine` class is used to specify the PM number, the slot number, and the channel number of a telephone line. It also indicates whether the line is busy or idle. Figure 2(b) illustrates the physical line configuration that corresponds to the telephone table layout in Figure 2(a).

3. MOBILITY MANAGEMENT FOR PBX

This section describes mobility management in a PBX environment. We assume that the reader is familiar with the concepts of mobility management. General discussions on mobility can be found in References [2–5].

Wireless extension to a PBX can be achieved by connecting radio base stations (BSs) to the PM. A BS with large capacity may connect to a DTU (digital trunk unit) card to provide an E1 link or 30 telephone connections (see (1) in Figure 3). A BS with small capacity can connect to LIUs (line interface unit) cards through several subscriber lines (see (2) in Figure 3). The small capacity BSs may also connect to a *radio extension* (RE) (e.g. radio port control unit in PACS [6]).

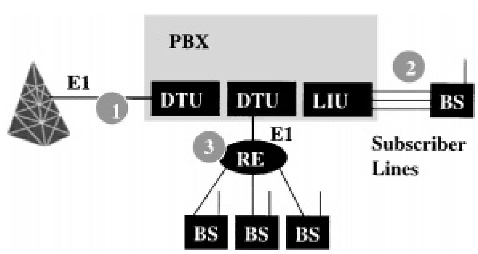

Figure 3. Wireless extension to the PBX.

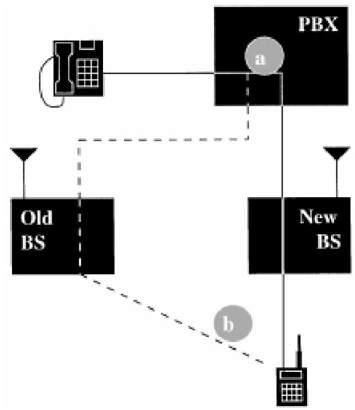

Figure 4. Handover.

The RE then connects to a DTU through the E1 trunk (see Figure 3 (3)). The PBX configuration described in the previous section must be modified in two aspects to accommodate wireless extension:

Mobility management: If a large number of BSs are connected to the PBX (e.g. 1000–2000 lines), they may be divided into *paging groups*. This concept is similar to the concept of registration area in cellular telephony [3–5]. Location update is required to indicate the paging group where a handset resides.

Handover: When a mobile user is in a conversation, the handset is connected to a BS via a radio link. If the user moves to the coverage area of another BS, the radio link to the old BS is disconnected and a radio link in the new BS is required to continue the conversation (see Figure 4(b)). The radio channel transfer will be taken care by the BSs. During this handover process, the PBX should reconnected the (wire) telephone line from the old BS to the new BS (see Figure 4(a)). Three-way calling feature can be used to implement handover at the PBX level. The descriptions are out of the scope of this paper. The reader is referred to [7] for more details.

To accommodate mobility management, two modifications to the PBX may be required:

PBX-BS interface. The BS will generate new types of signals to the PBX. There are two alternatives to accommodate these new signal types.

1. The DTU/LIU cards are modified to recognize the new signal types.
2. The BS is modified so that every new signal type is represented by the `Off-Hook` signal followed by a special code for DTMF signaling or the `Seizure` signal followed by a special code for trunk signaling [8,9].

We will elaborate the second alternative in this paper.

PBX software. A mobility management software should be created, and minor modifications to the call control process are required to implement mobility management.

We use the subscriber line connection (see Figure 3 (2)) to illustrate the implementation of wireless extension to the PBX.

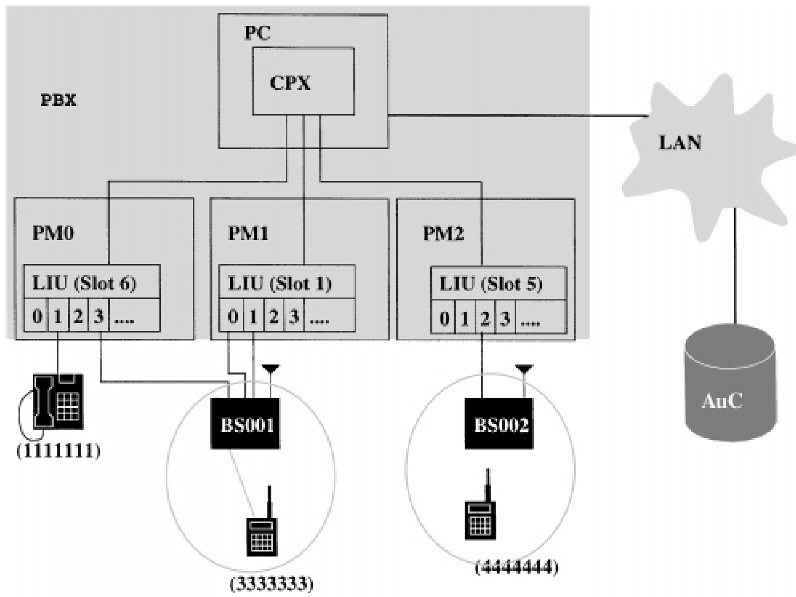

Figure 5. An example of wireless extension to the PBX.

For wireless extension based on the subscriber line connection (see Figure 5), a BS connects to the PBX through several subscriber lines. For a call originated from a handset in the BS coverage, an arbitrary idle subscriber line is selected by the BS to connect the PBX. For a call termination to a handset, the PBX selects an arbitrary idle line to the BS. We make the following assumptions.

Assumption 1. Every paging group consists of one BS. In other words, location update is performed every time a handset moves from a BS to another. For every call termination to a handset, at most one BS is asked to page the handset. We note that it is trivial to relax this assumption to accommodate multiple BSs in a paging group.

Assumption 2. Every BS has c_1 radio channels and c_2 wireline connections to the PBX where $c_1 \geqslant c_2$. If the BS is capable of handling intra-BS calls, then $c_1 > c_2$ in general. An intra-BS call does not need connection to the PBX as illustrated in Figure 6(a). If the BS cannot connect intra-BS calls by itself then the call is handled like an inter-BS call as illustrated in Figure 6(b). In this case $c_1 = c_2$. In our approach, a BS may inform the PBX whether it can handle intra-BS calls or not.

Assumption 3. An authentication centre (AuC) is required to authenticate the handsets. The AuC may or may not collocate with the PBX. The handset is authenticated via its password. This paper assumes that the AuC is implemented within the PBX.

Compared to the configuration in Figure 2(b), the configuration in Figure 5 introduces several new entities: handset (mobile phone), base station (BS), and authentication centre (AuC). The implementation for these entities are described below.

Line class. An abstract `Line` class is introduced. From this abstract class, two classes `WireLine` and `WirelessLine` are derived as illustrated in Figure 7. The `WireLine` class is the same as before except that an extra BS pointer is included (see Figure 8(a)). For a subscriber line

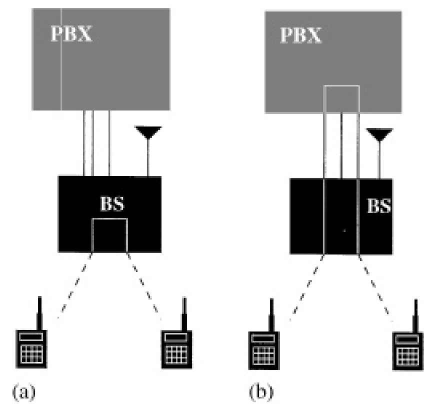

Figure 6. Intra-BS call connection: (a) BS with intra-BS switching ability; (b) BS without intra-BS switching ability.

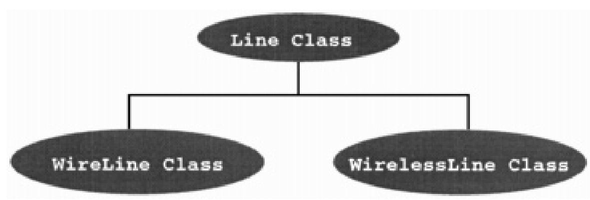

Figure 7. The Line class hierarchy.

connected to the wireline telephone, the BS pointer value is NULL. If a subscriber line is connected to a BS, then the corresponding WireLine object will point to the BaseStation object of the connected BS. Every WirelessLine object is associated with a handset. This class consists of three fields (Figure 8(f)): a status bit to indicate if the handset is busy, an AuC address (pointer to an authentication table where the handset's password is stored), a BS address (pointer to a BS object corresponding to the BS coverage where the handset resides).

BaseStation class. A BaseStation object maintains a circular linked list of pointers to the WireLine objects (Figure 8(b)). These WireLine objects correspond to the subscriber lines connecting the BS and the PBX. The BaseStation object also has a record to store the BS profile (encryption information, intra-BS call ability, and so on).

BSTable class. The BSTable object (Figure 8(c)) maintains the list of BSs connected to the PBX.

AuCTable class. The AuCTable object (Figure 8(d)) is a table that stores the authentication keys (passwords) of the handsets in the system. The authentication procedure is out of the scope of this paper but can be found in [3,10,11].

4. REGISTRATION PROCEDURES

When the PBX subscriber lines are first connected to a BS, BS line registrations are required (one registration per line). Consider BS001 in Figure 9. After channel 3 of Slot 6 in PM0 is connected,

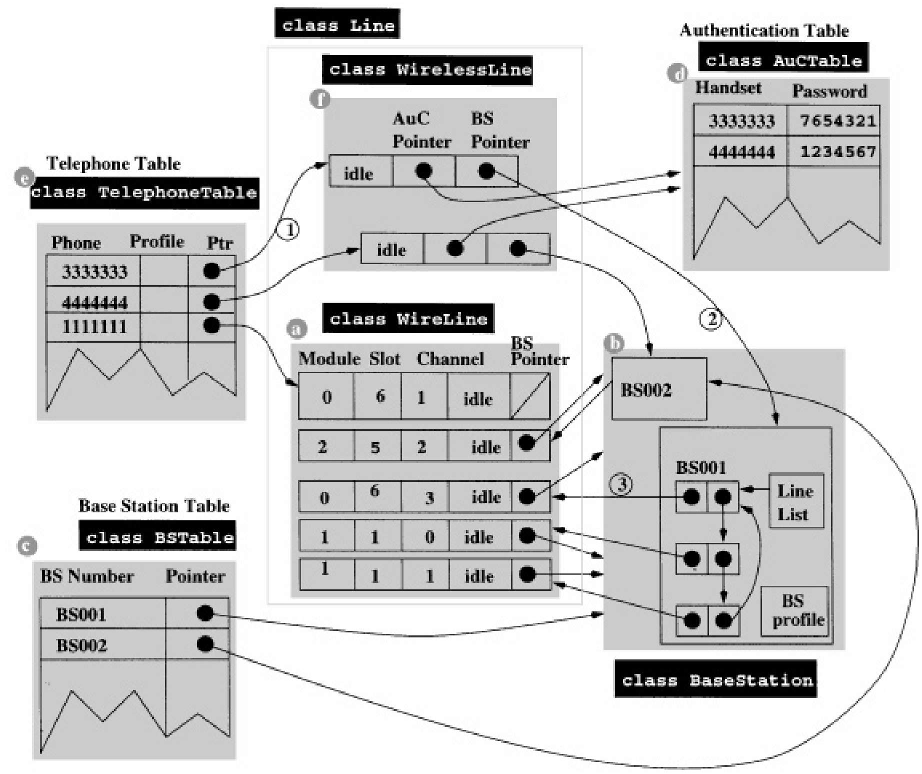

Figure 8. Data structures for mobility management.

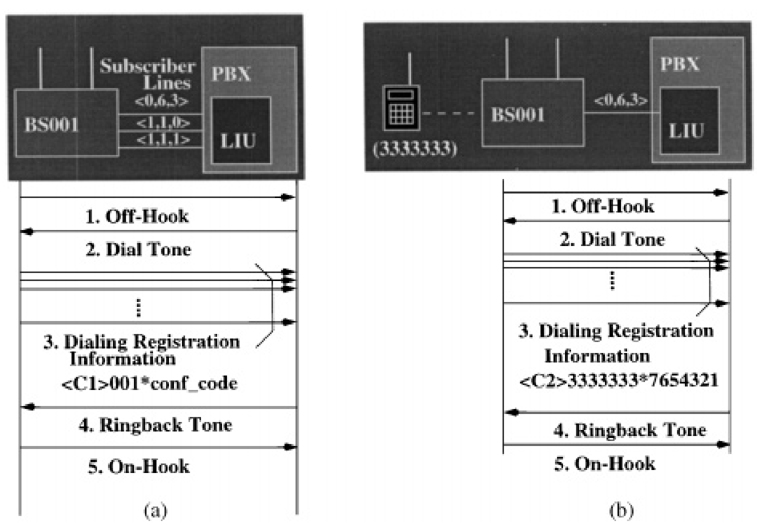

Figure 9. The BS and the handset registrations.

BS001 initiates the registration procedure through subscriber line signaling as illustrated in Figure 9(a). The BS line registration procedure is described in the following steps:

Steps 1 *and* 2. BS001 sends an Off-Hook signal to the PBX. The PBX replies dial tone to BS001, and expect to receive DTMF digits from BS001. Since these two steps are exact the same as that in the subscriber line call setup procedure, they are handled by the normal PBX call control process. At this point, a WireLine object $\langle 0, 6, 3\rangle$ is created (Figure 8(a)).

Step 3. BS001 sends a sequence of DTMF digits

$$\langle C1\rangle 001 * conf\_code$$

to the PBX where $\langle C1\rangle$ is a special sequence representing BS line registration, 001 is the BS number, and *conf_code* provides BS information such as the ability of handling intra-BS calls. This sequence is analysed by the Digit-Analysis procedure used in the normal PBX call control process. By detecting the code $\langle C1\rangle$, the BSTable (Figure 8(c)) is searched to locate the BaseStation object (Figure 8(b)) for BS001. If the BS001 entry is not found in the table, a new entry and a new BaseStation object BS001 is created for BS001. The WireLine object $\langle 0, 6, 3\rangle$ (Figure 8(a)) is added to the LineList of BS001, and the BS pointer field of the $\langle 0, 6, 3\rangle$ WireLine object is set to the address of BS001.

Steps 4 *and* 5. After the PBX has processed the DTMF digit sequence, it sends a tone signal (or a DTMF signal) to BS001. BS001 sends an On-Hook signal to complete the registration process. Note that if the PBX needs more information for the registration process, it may send a different DTMF signal to BS001. Based on the DTMF signal, BS001 may resend the DTMF string or abort the registration action.

The above procedure repeats for every subscriber line connected to BS001. For the data structures configuration in Figure 8, the corresponding physical layout is shown in Figure 5.

When a handset 3333333 arrives at BS001, a handset registration is required. The registration message flow is illustrated n Figure 9(b), and the steps are described below:

Steps 1 *and* 2. These steps are the same as that for BS line registration. BS001 selects an idle subscriber line for signalling. Suppose that the line is channel 3 of Slot 6 in PM0. At the end of Step 2, the WireLine object $\langle 0, 6, 3\rangle$ is identified by the PBX.

Step 3. BS001 sends the DTMF digit sequence

$$\langle C2\rangle 3333333 * 7654321$$

to the PBX where $\langle C2\rangle$ is a special sequence representing handset registration, 3333333 is the handset number, and 7654321 is the password. The Digit-Analysis procedure detects handset registration from the special code $\langle C2\rangle$ and searches the phone entry 3333333 in the TelephoneTable (Figure 8(e)). We note that all legal handsets are recorded in the TelephoneTable and the corresponding WirelessLine objects (Figure 8(f)) are created through an off-line procedure at system initialization. Thus, the telephone table entry is always found for a legal handset registration. Through the WirelessLine object, the handset is authenticated by using the number 7654321 in the DTMF string and the password stored in the AuCTable (Figure 8(d)). If the authentication process is successful, the BS pointer of the WirelessLine object is assigned the BS pointer value of the WireLine object $\langle 0, 6, 3\rangle$.

Steps 4 *and* 5. These steps are the same as Steps 4 and 5 in the BS line registration procedure.

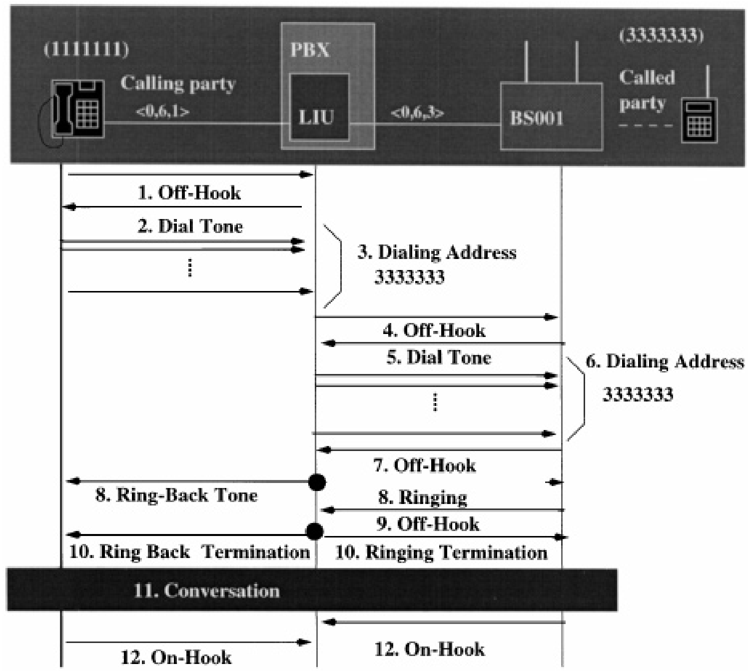

Figure 10. The wireline to wireless call.

5. CALL TERMINATION

Suppose that the wireline phone 1111111 calls the handset 3333333. The signalling procedure is illustrated in Figure 10.

Steps 1–3. These three steps are similar to that in the registration procedures in Figure 9. The difference is that the PBX recognizes the dialed DTMF digits as a phone number. The TelephoneTable object is searched to locate the WirelessLine object of 3333333 (see path (1) in Figure 11). If the search indicates that the handset is idle, then the PBX sets both the calling and the called Line objects 'busy' and locates the BaseStation object of the BS (i.e. BS001) where the handset resides (see path (2) in Figure 11). The PBX searches LineList of BS001 to find the first idle channel (⟨0, 6, 3⟩ in this example; see path (3), Figure 11).

Steps 4–6. Through the ⟨0, 6, 3⟩ WireLine object, the PBX informs BS001of the call termination to the handset 3333333. Steps 4–6 are similar to Steps 1–3. At the end of Step 6, BS001 pages the handset using the received handset number.

Step 7. If the handset (not the user of the handset) responds to the page, an Off-Hook signal (similar to the SS7 ISUP ACM message [12]) is sent from the BS to the PBX.

Step 8. The PBX sends a ringing tone to the called party (BS001), and a ring-back tone to the calling party (1111111).

Step 9. If the user of the handset 3333333 answers the phone, a second Off-Hook signal is sent from BS001 top the PBX.

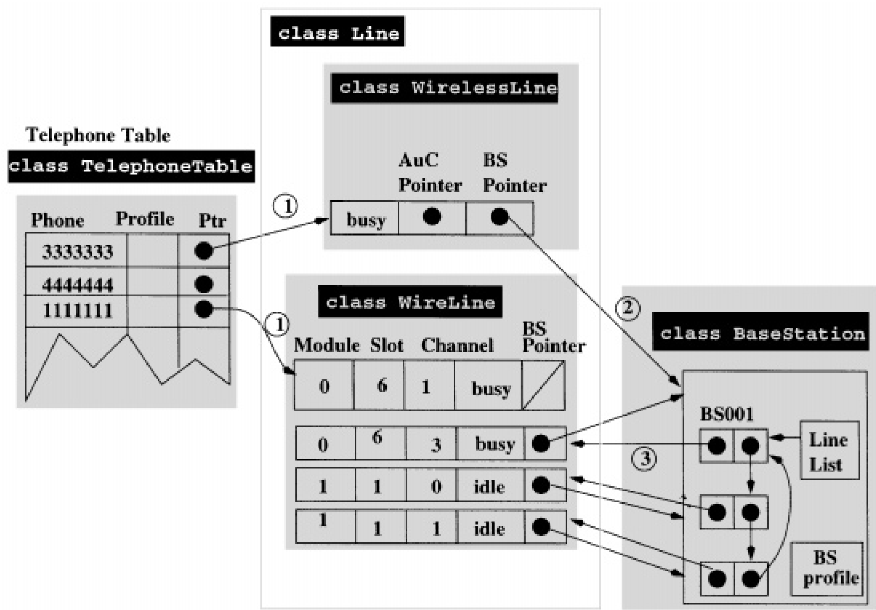

Figure 11. Data structure configuration for wireline-to-wireless call.

Step 10. The PBX detects the called party Off-Hook signal, and then removes the ringing and the ring-back tones.

Note that if the call set-up procedure fails for some reason, the Line objects correspond to 3333333 and 1111111 are marked 'idle' and the procedure is aborted. Otherwise, these objects are marked 'busy' at Step 3, and the procedure proceeds to Step 11.

Step 11. The voice path is connected and both parties start conversation.

Step 12. When either party hangs on, the On-Hook signal is sent to the PBX and the connection is released (the WirelessLine object for 3333333, the WireLine objects ⟨0, 6, 1⟩ and ⟨0, 6, 3⟩ are set 'idle').

Consider an intra-BS call where the calling handset 3333333 and the called handset 4444444 are both in the radio coverage area of BS001. If the BS cannot switch the intra-BS call, then the signaling and switching procedure is exact the same as that in Figure 10. If the BS can handle the intra-BS call without subscriber line set-up through the switch, then the signalling procedure is illustrated in Figure 12.

Steps 1–3. These three steps are similar to that in the handset registration procedure in Figure 9(b). BS001 selects ⟨0, 6, 3⟩ for all origination signalling to the PBX. The PBX marks the WireLine object ⟨0, 6, 3⟩ 'busy' and recognizes the dialed DTMF digits as a wireless handset call origination (represented by the special code ⟨*C*3⟩) where the calling handset number is 3333333, its password is 7654321, and the called party number is 4444444. The TelephoneTable is searched to locate the WirelessLine object of 3333333 (see path (1) in Figure 13). Suppose that the line object indicates the idle status. The status is marked 'busy'. The BS pointer of the object is

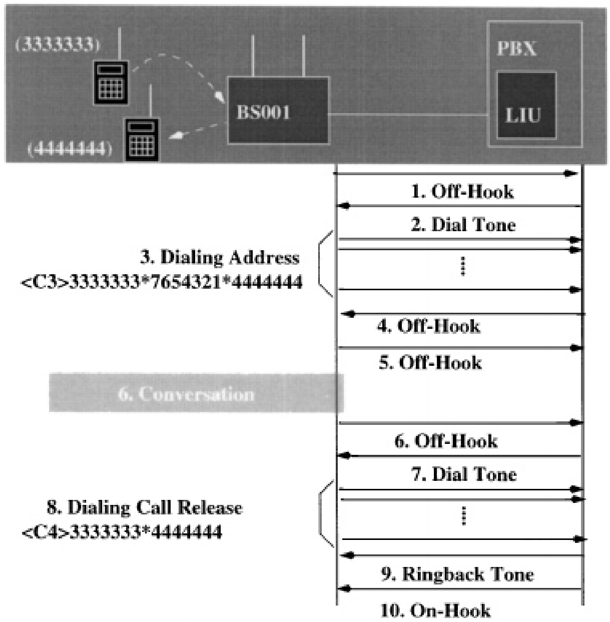

Figure 12. The intra-BS call signalling procedure.

used to compare with the BS pointer of the WireLine object ⟨0, 6, 3⟩. If they do not match, then an error is detected. This situation occurs when a handset makes a call at a BS before it registers to that BS. The authentication procedure is performed as described in the registration procedure (see path (2) in Figure 13). Then the Line object of the called handset is located as described at Step 3 of the wireline-to-wireless call procedure (see path (3), Figure 13). The PBX realizes that both the calling and the called parties are in BS001.

Steps 4 *and* 5. Through the same subscriber line ⟨0, 6, 3⟩, the PBX informs the base station BS001 of an intra-BS call using the Off-Hook signal. BS001 pages 4444444, and connects 3333333 to 4444444 directly. BS001 informs the PBX that the call is set up by an Off-Hook signal. At this point, both Line objects for 3333333 and 4444444 are 'busy'. The PBX sets ⟨0, 6, 3⟩ 'idle'.

Step 6. The conversation begins without using any subscriber line between BS0001 and the PBX.

Steps 7–10. At the end of the conversation, BS001 releases the radio channels, and sends a DTMF sequence with the special code ⟨*C*4⟩ to the PBX. The code represents 'end of intra-BS call'. Based on the handset numbers (3333333 and 4444444), the PBX marks the corresponding WirelessLine objects 'idle', which completes the intra-BS call transaction.

6. PERFORMANCE ISSUES

Signalling traffic due to mobility may degrade the performance of the PBX. Our experience with the computer-controlled PBX is that the extra CPU processing cost for mobile operations

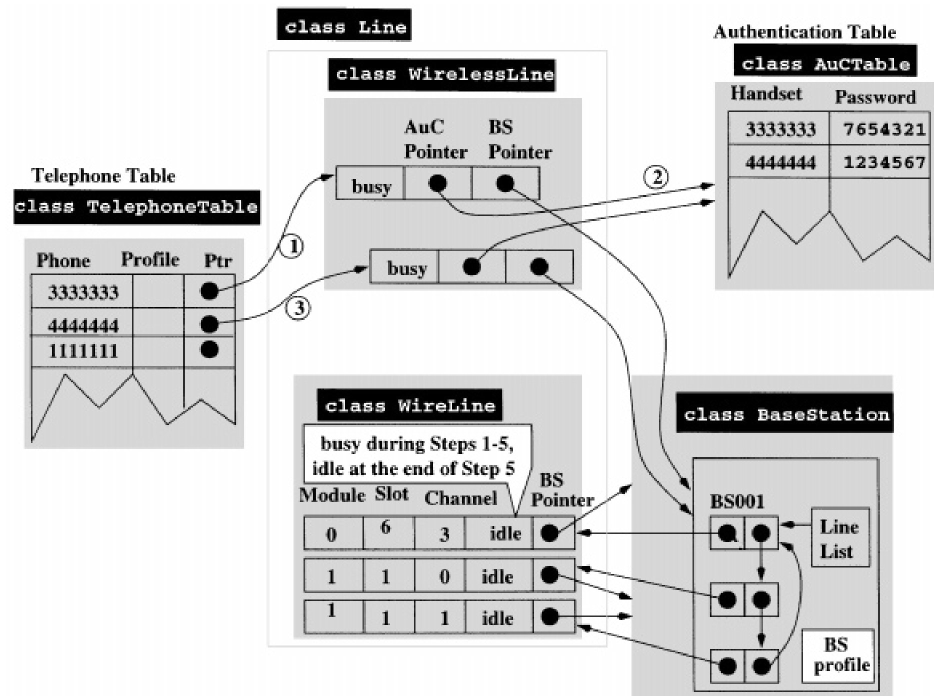

Figure 13. Data structure configuration for intra-BS call.

(specifically, registrations and wireless call terminations), are negligible compared with the normal call-set-up processing cost.

A potential problem occurs when handset registration utilizes a subscriber line from the BS to the PBX. If all subscriber lines are busy when a registration request arrives, the system may simply drop the registration. On the other hand, we can still allow registration operation by sending DTMF signalling through a busy line. In this case, the user of the subscriber line will hear the DTMF tone during the conversation. Such DTMF 'noise' may be considered as degradation of circuit quality. Thus, it is important to see how often a busy line is interrupted by the registration operations. We propose an analytic model to investigate this issue. Suppose that the call arrivals are Poisson process with rate λ, and the call holding times are exponentially distributed with mean $1/\mu$. If there are c subscriber lines between the BS and the PBX, then the probability p_b that all subscriber lines are busy can be expressed by the Erlang B formula

$$p_b = \frac{(\rho^c/c!)}{\sum_{0 \leqslant j \leqslant c} (\rho^j/j!)}$$

where $\rho = \lambda/\mu$. Suppose that the registration traffic forms a Poisson process with rate γ. The rate of registration traffic that will interrupt a particular line (with probability $1/c$) is thus

$$\theta = \frac{\gamma p_b}{c} \tag{1}$$

Table I. The number of registration interruptions to a call ($c = 8$).

λ/μ	4.0	5.0	6.0	7.0	8.0
p_b (%)	3.04	7.00	12.19	17.88	23.56
$E[K]$ ($\gamma/\mu = 0.5$)	0.001898	0.004359	0.007560	0.011053	0.014510
$E[K]$ ($\gamma/\mu = 1.0$)	0.003788	0.008680	0.015006	0.021864	0.028604
$E[K]$ ($\gamma/\mu = 1.5$)	0.005671	0.012964	0.022341	0.032441	0.042301

From (1), the number k of registrations that will affect a call during its call holding time t_h has a Poisson distribution with density function

$$f_k(t_h) = \frac{(\theta t_h)^k}{k!} \mathrm{e}^{-\theta t_h}$$

The probability $\Pr[K = k]$ that there are k registration interruptions to a call is

$$\begin{aligned} \Pr[K = k] &= \int_{t_h=0}^{\infty} f_k(t_h)\, \mu \mathrm{e}^{-\mu t_h}\, \mathrm{d}t_h \\ &= \left(\frac{\theta^k}{k!}\right) \int_{t_h=0}^{\infty} t_h^k\, \mu \mathrm{e}^{-(\theta+\mu)t_h}\, \mathrm{d}t_h \\ &= \left(\frac{\theta^k}{k!}\right) \left[\frac{\mu k!}{(\theta+\mu)^{k+1}}\right] = \frac{\mu\theta^k}{(\theta+\mu)^{k+1}} \end{aligned} \qquad (2)$$

From (2), the expected number $E[K]$ of registration interruption to a call is

$$E[K] = \sum_{i=1}^{\infty} i \Pr[K = i] = \frac{\gamma p_b}{c\mu + \gamma p_b} \qquad (3)$$

Table I lists the number $E[K]$ of registration interruptions to a call for various call and registration traffics where $c = 8$. Suppose that the mean call holding time is $1/\mu = 3$ min. For the worst case in the table (where the call arrival rate is 2.67 calls per minute and the registration rate is 0.5 per minute), the probability p_b of no idle circuits is 23.56% and the expected number of interruptions to a call is less than 0.05. The above analysis indicates that under reasonable conditions, the PBX calls are seldom affected by the mobility traffic.

7. CONCLUSION AND FUTURE WORK

This paper proposed a PBX-based mobility manager that can be used in a WLL to offer user roaming capability within the WLL service area. We showed how this design can be implemented in an environment where the PBX and the BSs are connected through analog subscriber lines (the design can be easily modified to accommodate other telephone circuit interfaces). At the current stage, we have implemented all mobility management software. The authentication centre for the WLL is implemented in a separate server that connects to the PBX through Ethernet using TCP/IP. The PBX is connected to a radio system emulator to drive the software. The emulator will be replaced by a DECT system and/or a PACS system. One future direction of our work is the development of multiple-PBX WLL system. In such an architecture, mobility management will evolve into a GSM or IS-41-like two-level mobility database hierarchy [4, 5]. As a final remark, we note that in the multiple-PBX configuration, the service areas of two PBXs typically do not overlay. Thus, inter-PBX handover are not considered in most WLL products.

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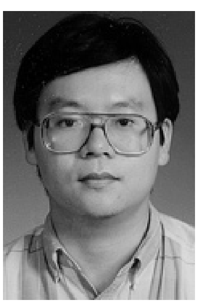
AUTHOR'S BIOGRAPHY



Yi-Bing Lin received his BSEE degree from National Cheng Kung University in 1983, and his PhD degree in Computer Science from the University of Washington in 1990. From 1990 to 1995, he was with the Applied Research Area at Bell Communications Research (Bellcore), Morristown, NJ. In 1995, he was appointed as a professor of Department of Computer Science and Information Engineering (CSIE), National Chiao Tung University (NCTU). In 1996, he was appointed as Deputy Director of Microelectronics and Information Systems Research Center, NCTU. Since 1997, he has been elected as Chairman of CSIE, NCTU. His current research interests include design and analysis of personal communications services network, mobile computing, distributed simulation, and performance modelling. Dr Lin is an associate editor of IEEE Network, an associate editor of SIMULATION magazine, an area editor of ACM Mobile Computing and Communication Review, a columnist of ACM Simulation Digest, a member of the editorial board of International Journal of Communications Systems, a member of the editorial board of ACM/Baltzer Wireless Networks, a member of the editorial board of Computer Simulation Modelling and Analysis, an editor of Journal of Information Science and Engineering, Program Chair for the 8th Workshop on Distributed and Parallel Simulation, General Chair for the 9th Workshop on Distributed and Parallel Simulation. Program Chair for the 2nd International Mobile Computing Conference, the publicity chair of ACM Sigmobile, Guest Editor for the ACM/Baltzer MONET special issue on Personal Communications, and Guest Editor for IEEE Transactions on Computers special issue on Mobile Computing. Lin received 1997 Outstanding Research Award from National Science Council, ROC, and Outstanding Youth Electrical Engineer Award from CIEE, ROC. Lin's E-mail address is liny@csie.nctu.edu.tw.

