Personal Access Communications System: Fixed Wireless Local Loop and Mobile Configurations and Services

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The Personal Access Communications System (PACS) supports wireline quality voice, voiceband data, digital data, and messaging services and is based on a low-power, low-complexity design. Operating environments for PACS include indoor and outdoor; fixed, low mobility, and vehicular mobility; and private and public access. PACS is a microcellular system providing high frequency reuse efficiency and thus is capable of supporting high traffic density. These attributes make PACS ideal for providing fixed wireless local loop and mobile services in moderate to densely populated areas, including developing countries. PACS mobile and fixed wireless local loop service can be offered by interfacing PACS with advanced intelligent network/integrated services digital network switches, any traditional wireline switches, or with cellular/personal communications system mobile switching centers. The PACS air interface has been standardized by the American National Standards Institute.

Keywords—*Local loop, network interface, personal communication systems, wireless access.*

I. INTRODUCTION

The copper pair that connects a telephone subscriber's premises to the telephone network has proven to be a highly effective and cost-competitive means of linking the customer to the feature-rich telephone central office switch. Not many alternatives exist that can compete in cost and services with that provided between the subscriber and the network by the pair of copper wire conductors designated as tip and ring. In many developing countries, wireless access is the viable means to meet the high demand for basic telephone service. Digital wireless technologies initially designed for mobile cellular or personal communications system (PCS) applications are proving cost-effective alternatives to the traditional copper cables. However, they do so by providing a reduced set of features along with a drop in local loop circuit quality. The choice of wireless technology and the system characteristics dictate the breadth of services available to the subscriber, the quality level of the service, and the economics to both the subscriber and the system operator.

The Personal Access Communications System (PACS) [1]–[3] can provide a wireless alternative to wired local loop for both mobile and fixed wireless local loop (WLL) services while providing all of the services with the same quality as the existing wireline network. PACS may be used in areas with no available telephone service to provide rapid deployment of basic telephone service. In areas with telephone service, PACS may be used by a competitive service provider to offer WLL services without the subscriber's noticing any change in quality or services. All of the existing customer premises equipment (modems and phones) that worked on the copper pair will also operate in the same way on the WLL. There exists a high synergy between the PACS architectures designed to offer WLL services and mobile services. Therefore, a WLL service has a small marginal cost when added to a mobile service or the mobile service has a small marginal cost when added to a WLL service.

This paper provides an overview of PACS technology for WLL and mobile services. Section II provides an overview of the PACS system concepts. Section III discusses the options for interfacing a PACS system with the wireline network. PACS services are discussed in Section IV. Section V discusses the wireless fixed access unit (WAFU) functions and maintenance features.

II. PACS SYSTEM CONCEPTS

PACS is one of the American National Standards Institute (ANSI) air interface standards for the 1.9-GHz PCS band in the United States. [4]. The PACS air interface was standardized by the Joint Technical Committee of the Telecommunications Industry Association (TIA) and

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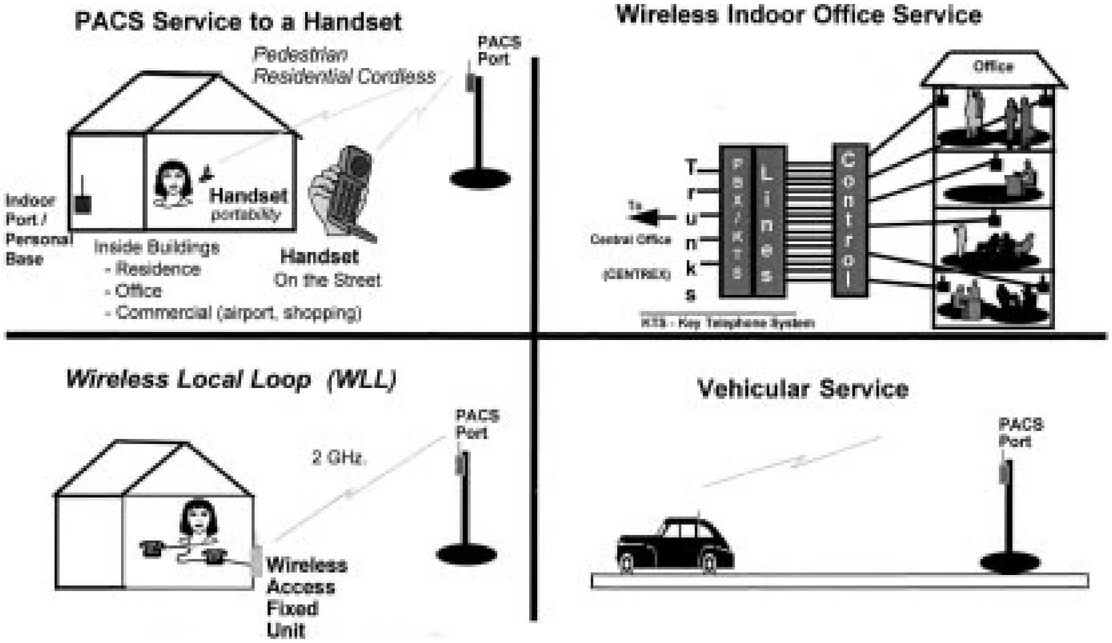

Fig. 1. PACS operating environments.

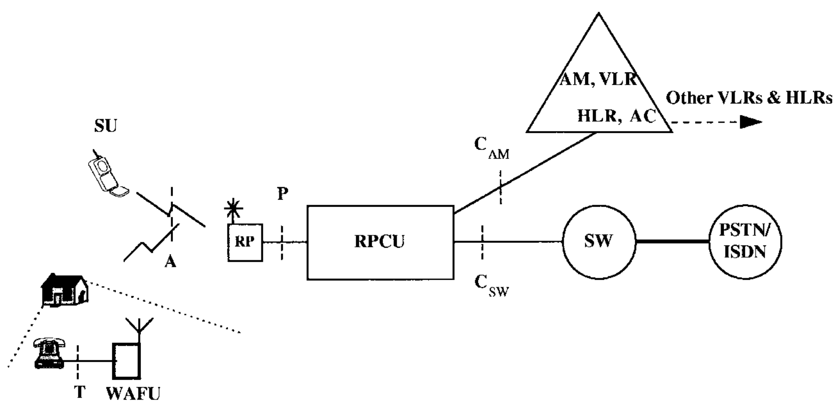

Fig. 2. Functional representation of PACS architecture.

the Alliance for Telecommunications Industry Solutions Committee T1. The PACS air interface standard has a frequency division duplexing (FDD) mode to enable operation in a licensed frequency allocation and a time division duplexing (TDD) mode [5] to enable operation in an unlicensed frequency allocation. PACS provides wireline quality voice at extremely low radio link delay. PACS is a low-complexity system providing high frequency reuse efficiency and thus is capable of supporting high traffic density. These attributes make PACS ideal for providing WLL and mobile services in densely populated urban areas and in developing countries.

PACS supports wireless access telecommunications services in several operating environments. These environments include indoor and outdoor, WLL, low and vehicular mobility, and private and public access, as shown in Fig. 1. The WLL application pertains to situations where a wireless drop connection to the customer premises may be preferable (for economic or other reasons) to a wireline connection. Low-mobility applications include outdoor pedestrian (public wireless access), indoor residence (home cordless), indoor business [wireless private branch exchange (PBX)], and indoor commercial applications (wireless access in airports, railway stations, shopping centers, etc.). PACS can also support vehicular mobility typical of the traditional cellular networks. In addition, PACS can support any combination of operating environments in the same service area.

A. Functional Architecture

The functional representation of the PACS system is shown in Fig. 2. The architecture consists of wireless access fixed units (WAFU's) or portable subscriber units (SU's) communicating with radio ports (RP's) over the air. The RP's are connected to the RP control units (RPCU's), which interface to the public switched telephone network (PSTN). The access manager (AM) assists in managing the radio resources used for mobility management. Call control functions are provided by wireline switches. Mobility of users is supported by the mobility management network consisting of the visited location register (VLR), the home location register (HLR), and the authentication center (AC).

The functional elements of the PACS architecture are described below.

Portable SU's are wireless terminals that perform the necessary functions to provide speech and data services to the user. WAFU's provide interworking between conventional analog customer premises equipment (e.g., telephones, modem, fax machines) and PACS air interface protocols.

The RP provides a link between SU's and the RPCU and functions as a simple radio modem. No processing takes place on a per-call basis in the RP. The functions in the RP include transmission/reception of radio signals, modulation/demodulation, channel coding/decoding for error detection and burst synchronization, clock regeneration and synchronization, interfacing to the fixed network transmission facilities, and self-diagnostics capabilities. The RP continuously monitors the receive signal quality of the radio link with the SU and transmits the information back to the RPCU for processing.

The RPCU provides management and control functions between the RP and the fixed network. The RPCU functions include time division multiplex (TDM) framing, multiplexing/demultiplexing between multiple RP's and the network, transcoding between air interface codec and wireline codec, enciphering/deciphering traffic channels for privacy, echo treatment, power control, managing spectrum allocation, and processing automatic link transfer (ALT)/handoff requests from the SU. The RPCU provides the interfaces to such network systems as may be necessary to support PACS services. These interfaces will vary depending on the nature of the telephony network into which PACS interworks.

The AM, in conjunction with the RPCU, assists in managing the radio resources used for mobility management. It provides the storage, maintenance, access, and control of data and interacts with other network elements to provide wireless service. The AM may be implemented in the RPCU or in a switch adjunct, or its functionality may be implemented in an advanced intelligent network (AIN) service control function.

The mobility functions are supported by the VLR, HLR, and the AC. The VLR provides a location register that maintains the user profiles with information obtained from the HLR for the SU's registered in its area. The VLR mediates the service requests between the HLR and the AM currently serving the user. The HLR contains the service logic, end user's service profiles, and location registers that track where the end users are currently registered. The AC stores the permanent keys of users and generates temporary keys for authenticating users and encrypting the radio link. For WLL services, the functions of the AM, VLR, HLR, and AC may be provided by a fixed location register (FLR).

B. PACS Interfaces

PACS provides open interfaces between different functional elements to permit a system composed of equipment from multiple suppliers. The interfaces are shown in Fig. 2.

The T interface supported by the WAFU is similar to the subscriber loop interface supported by a local switching system. However, the WAFU supports a relatively short loop between the WAFU and the attached analog instruments that are confined within the customers' residence or business.

The A interface (the "air interface") connects the WAFU or SU and the RP. Two versions of the PACS air interface exist, one using FDD and the other using TDD. The FDD version is more suitable for outdoor environments and for when the spectrum allocation consists of two blocks of spectrum separated by 50 MHz or more. The TDD version is more suited for business indoor and residential cordless applications or for when the spectrum allocation is one block of spectrum.

The P interface provides connectivity between the RPCU and its RP's. The physical interconnection (layer 1) between the RPCU and its RP's may be implemented in any of several means. Physical transmission facility options for the P interface include $E1$, $T1$, and high-speed digital subscriber line (HDSL) and DSL technologies. Choice of an interface for a specific application depends on several parameters, including the number of voice circuits being implemented at the RP, the distribution media available, the distance between the RP and the RPCU, and the cost of the distribution facility.

The C_{sw} interface provides connectivity between RPCU's and the PSTN. Where available, the C_{sw} interface can use an integrated services digital network (ISDN) basic rate interface (BRI). The RPCU can also be connected to a cellular/PCS mobile switching center (MSC) or to a non-ISDN network. Various options for interfacing the RPCU with the PSTN are described in Section III. The C_{AM} interface provides mobility management signaling between the RPCU and the AM.

Signaling among the RPCU, AM, and VLR may use ISDN, transmission control protocol/Internet protocol (TCP/IP) network, Signaling System 7 (SS7) network, X.25, or other transport options. The signaling protocol used between the RPCU and the AM and between the AM and the VLR is the mobility management application protocol [6], [7]. Signaling among the VLR, HLR, and AC is done over the SS7 network, and the protocol used is the IS-41 mobile application protocol (MAP) [8].

C. PACS Air Interface Characteristics

The characteristics of the PACS air interface are briefly outlined in this section. The PACS system, whether used for mobile service or WLL service, has the same air interface characteristics, thereby permitting mobile and WLL services to coexist on the same system.

1) Frame Structure: PACS employs TDM in the downlink from the RP to the SU and time division multiple access (TDMA) in the uplink. The channel spacing is 300 kHz. A basic frame structure of 2.5 ms is employed in order to minimize speech transmission delay [9]. Each frame is made up of eight bursts. Each burst carries 80 bits of user information, 10 bits of control information, and 15 bits of cyclic redundancy check. The overall bit rate is 384 kb/s that is transmitted at 192 ksymbols/s.

2) Frequency Planning: RP operating frequencies are assigned manually or autonomously. Autonomous assignment eliminates the need for precise frequency planning. The autonomous frequency assignment is called the quasistatic autonomous frequency assignment (QSAFA) process [10]. QSAFA is a self-regulating means of selecting individual RP frequency channel transmit/receive pairs that functions without centralized frequency coordination between different RP's. The QSAFA process is controlled by the RPCU for its associated RP transceivers. QSAFA combines the principal advantage of dynamic channel allocation with the performance advantages of a fixed frequency assignment.

3) Radio Link Maintenance: Both SU and RP are required to take measurements to monitor its RF environment. The three measures considered for link maintenance are the received signal strength indicator (RSSI), quality indicator (QI), and word error indicator (WEI). The RSSI is a measure of cochannel interference power and noise in unoccupied time slots. The QI is the estimate of the "eye opening" of a radio signal, which relates to the ratio of signal to interference plus noise, including the effects of dispersion. The WEI is an indication of whether one or more bit errors occur in a time slot due to any radio link degradation.

These measurements are used for automatic link transfer (ALT) or handoff, time slot transfer (TST), and power control. The SU determines when and to which RP to perform ALT or TST. The SU output power is controlled by the RPCU by using power control. PACS employs SU-controlled ALT. The ALT and TST decisions are made by the SU in order to offload this task from the network and to ensure robustness of the radio link by allowing reconnection of calls even when radio channels suddenly become poor.

4) System Broadcast Channel: The channel designated for broadcasting the system information, alerting information, and responses to priority access is the system broadcast channel (SBC) [11]. The SBC has a superframe length of 1 s, where each superframe is divided into a number of alert phases. The SBC superframe (and therefore, each alert phase) repeats periodically at 1-s intervals and provides a reference for the SU's to wake up to listen to the alerting information. The alerting information, system information, and responses to priority access are dynamically multiplexed onto the SBC. The SBC may be designated at 32, 16, 8, or 4 kbps.

5) Registration/Deregistration: Registration is the process by which SU's inform the network of their current location, i.e., registration area (RA). When an SU enters an RA, either when it is powered on or when it moves between RA's, it registers at the VLR, and the address of the new RA is reported to the HLR of the SU. To locate an SU, its HLR is accessed to find the current VLR address of the SU. PACS allows multiple types of registration/deregistration procedures that are used to support a range of enhanced features.

6) Alerting Protocol: An alerting protocol is used to inform an SU of an incoming call. PACS uses a novel alerting protocol that optimizes the alerting bandwidth and increases the standby time of the SU [11]. Each SU is assigned a unique alert identification (ID) within the registration area. The alert ID consists of two parts: the alert phase and the alert value. Each SU periodically wakes up during its alert phase and listens for its alert value. If the SU does not hear its own alert value, it returns to the sleep mode. The protocol allows over 200 000 SU's in an alerting area using a 16-kbps SBC.

7) Privacy and Authentication: The goal of the PACS privacy and authentication is to make it impractical for an impersonator to obtain service or for an eavesdropper to listen to the radio link [12]. SU authentication verifies that a proffered SU identifier is true. Network authentication is a process whereby an SU ensures that an accessed network RP is legitimate. Network authentication is required to prevent potential fraud perpetrators from impersonating a network RP. PACS security addresses the following issues.

- *Authentication and key agreement (AKA) protocol:* PACS supports either a public-key AKA protocol or a private-key AKA protocol.
- *Radio link encipherment:* This process protects radio information against interception by eavesdroppers. Privacy of a traffic channel is guaranteed by radio link encipherment. The cipher requires a session key. For a newly initiated channel, the session key is generated by the AKA protocol.

8) Licensed and Unlicensed PACS Interoperability: The PACS air interface protocol supports a TDD version for use in the unlicensed frequency allocation [5]. Unlicensed PACS finds important applications in private access (e.g., home cordless, wireless PBX, etc.). Unlicensed PACS is based on the PACS licensed version with modifications to the physical layer to conform to the Federal Communications Commission etiquette rules for the unlicensed spectrum. Both versions share much of the higher layer protocols for terminal interoperability. The air interface rate, frame length and structure, signaling protocol, and channel bandwidth are similar for both systems, and the hardware impact is minimal.

III. PACS-TO-PSTN INTERFACE OPTIONS

PACS was originally developed under the assumption that it would be interfaced to an AIN/ISDN switch. In this case, routing and call control functions are supported by the switch, and mobility management functions are supported by AIN capabilities of the PSTN and IS-41 MAP. Mobile and WLL services offered using this architecture have the subscriber features controlled by the HLR. Many new PCS operators may want to quickly offer WLL in areas where the required AIN capabilities are either not yet available or not being planned at all (e.g., in developing countries). In addition, it may be desirable to offer features based on the switch, as wireline switches have extensive services and features that have emerged as a result of the billions of dollars of software development investments over the past several decades. The following sections describe the two

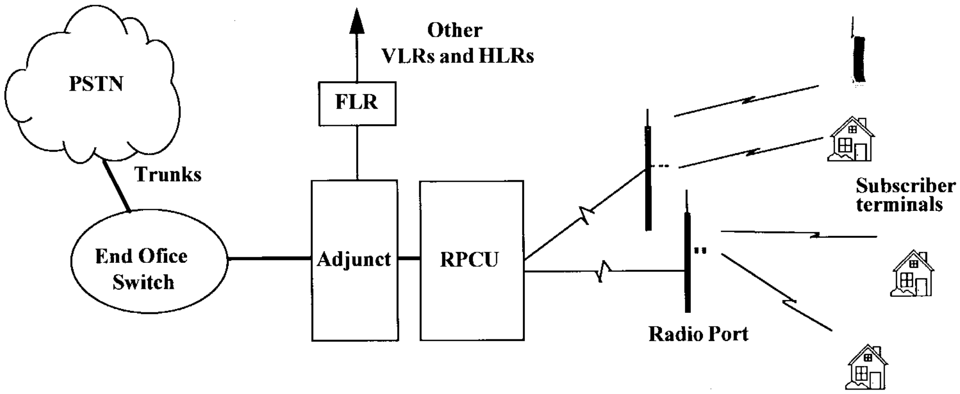

Fig. 3. PACS system with features derived from the wireline switch.

alternatives for offering mobile and WLL services. They are a) PACS system with features derived from the wireline switch and b) PACS system with features derived from the HLR.

A. PACS System with Features Supported by the Wireline Switch

Fig. 3 shows the architecture for interfacing a PACS WLL system with any end office switch (analog or digital) and deriving features from the switch. Since PACS was originally designed to interface to an AIN/ISDN switch, an adjunct is required between the RPCU and the switch when PACS is interfaced with a non-AIN switch. The adjunct emulates some of the functionalities of the AIN/ISDN switch. The functionalities of the adjunct include translating the ISDN call control signaling used by the RPCU to the signaling used by the switch and routing the mobility signaling between the RPCU and the mobility network. The adjunct functionality may be integrated with the RPCU.

Various options are available for interfacing the adjunct with the switch. Available options include GR-303 interface [13] with fixed assignment or dynamic assignment providing concentration. The FLR is a data base that provides the functionalities of the AM, VLR, HLR, and AC. For mobile users, the FLR also acts as an AM/VLR.

The above architecture can be extended when the end office switch is AIN/ISDN capable. In this scenario, the adjunct is no longer required, and the FLR functionality may reside in the AIN SCP.

This architecture is more suited for WLL service offering, though mobile service may also be offered. Mobility of the users is limited to the coverage area of the RPCU. Roaming support for users visiting from other networks may also be offered. The highlights of this architecture are as follows.

- The architecture allows interfacing the PACS system with any traditional wireline office switch (analog or digital).
- The PACS WLL connection to the subscriber premises is transparent to the switch. The switch sees a line appearance (a line/subscriber).
- WLL subscriber profiles and services reside in the switch with no impact caused by the PACS WLL.
- All switch-based services can be supported for the WLL subscribers.
- The architecture supports cost-effective concentration between the switch and the RPCU (or adjunct) using GR 303.
- The FLR handles the authentication and privacy functions for WLL and mobile users.
- Mobility management signaling between the adjunct and the FLR may use any available transport (e.g., TCP/IP, X.25, etc.).

B. PACS System with Features Supported by the HLR

When PACS is deployed for mobility services, the subscriber feature profile is stored in the HLR. This allows a subscriber roaming to a visited system to obtain the same services as in the home system (if offered by the visited system). WLL service may be offered using the same architecture, where a WAFU will appear as a mobile subscriber to the PACS network. Two possible configurations are a) PACS interfaced to an AIN/ISDN switch and b) PACS interfaced to a cellular/PCS switch.

1) PACS System Interfaced to an AIN/ISDN Switch: Fig. 4 shows the architecture when PACS is interfaced to an AIN/ISDN switch and features are derived from the HLR [14].

The architecture is more suited for mobile service offering, though WLL service may also be offered. The highlights of this architecture are as follows.

- The architecture makes use of the AIN capabilities of the switch to provide control channels between the RPCU and AM to facilitate mobility for the mobile users.
- Subscriber feature and service profiles reside in the HLR. The features and services for WLL subscribers are restricted to the feature sets available from the HLR manufacturer.
- Wide-area roaming and mobility are supported for all mobile subscribers.
- The AM in association with VLR, HLR, and AC handles the authentication and privacy functions for WLL and mobile users.

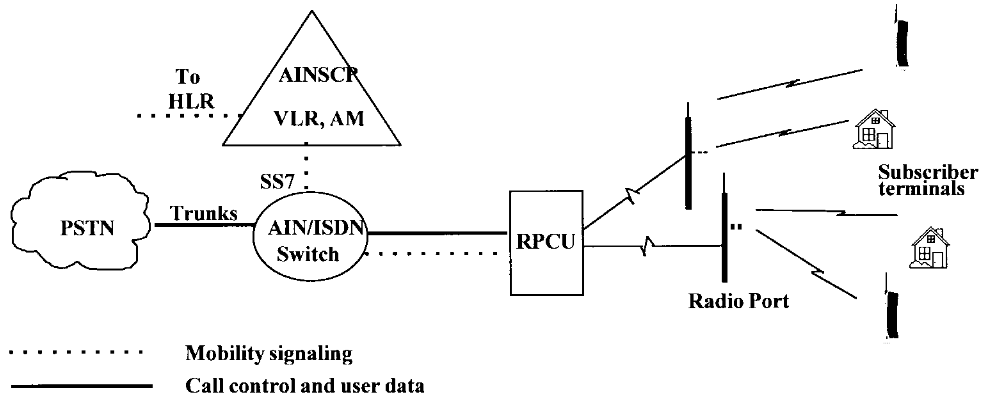

Fig. 4. PACS system interfaced to an AIN/ISDN switch.

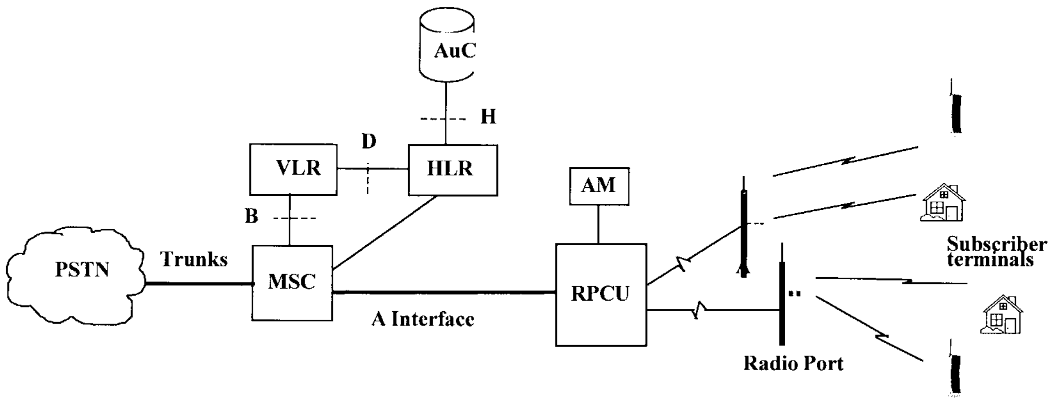

Fig. 5. PACS system interfaced to a cellular/PCS MSC.

- Mobility management signaling between the RPCU and the AM may use ISDN noncall associated signaling or other transport options.

2) PACS System Interfaced to a Cellular/PCS MSC: When an extensive cellular/PCS network is available, it may be more convenient to interface the PACS system with a cellular/PCS MSC [15]. This scenario is illustrated in Fig. 5.

The architecture is more suited for mobile service offering, though WLL service may also be offered. The highlights of this architecture are as follows.

- The architecture allows a PACS network to be interfaced to a cellular/PCS network on the A-Interface.
- The RPCU, along with the AM, performs the interworking between the cellular/PCS network and the PACS network.
- Additional PACS air interface messages may need to be supported.
- The RPCU uses cellular/PCS A-Interface compatible call control mobility management messages.
- Subscriber profiles reside in the cellular/PCS HLR.
- Mobility and wide-area roaming are supported by the cellular/PCS mobility management protocols. All the WLL and mobility features are defined by the cellular/PCS HLR.

IV. PACS Services

The PACS technology supports a wide range of WLL and mobile services and has the capability to evolve as the wireline and wireless network infrastructure expands its features and services. The services include those enumerated below.

A. Voice Services

1) Toll-Quality Voice: PACS offers toll-quality voice using ITU-T G.726, adaptive differential pulse code modulation (ADPCM), at 32 kbps as the default coding scheme [16]. This bearer service is used primarily for speech information transfer, and it is not intended to support voiceband modems, although it may provide support of up to 4.8-kbps voiceband modems. ITU-T G.728, 16-kbps low-delay code-excited linear prediction, is specified as an option [17]. The 16-kbps codec permits a more efficient use of the radio spectrum and is intended for voice only.

2) Voice Band Data: PACS provides a 64-kbps PCM connection by aggregating multiple time slots. This service is equivalent to the PCM voice used in the wireline network. This bearer service is primarily used to support all voiceband modems, including 56-kbps modems. The 64-kbps circuit-switched service is provided by every fixed network and can be fully interconnected with analog and digital telephone networks without the need for interworking functions. If a voice connection was established at 32 or 16 kbps and PACS detects the presence of voiceband data, it automatically changes the bearer to a 64-kbps PCM connection.

B. Data Services

PACS supports a rich set of data services. Data services supported include circuit-mode data, messaging, and packet-mode data, as well as interleaved speech/data.

1) Circuit-Mode Data Services: The circuit-mode data service is a nontransparent-mode data service in which data are enciphered for privacy and the data integrity is protected by an error and flow control protocol, link access protocol for radio (LAPR) [18]. LAPR is primarily based on link access procedure for modems as defined by ITU-T V.42 but optimized for the PACS radio channel. LAPR operating in a 32-kb/s channel provides a data throughput of more than 28 kb/s at wireline error rates. Higher speed data transmission can be achieved by aggregating multiple time slots. LAPR supports multiple simultaneous logical links on a single bearer channel, each distinguished by a data link connection identifier.

a) 64 kbps dialed circuit ISDN B-channels: This is a dialed digital call that supports the various ISDN B-channel bearer capabilities. If the PACS connects to an ISDN switch, the subscribers can place dialed digital calls over the PACS access network to the ISDN switch that supports the B-channel bear modes of service.

b) ISDN basic rate interface: The BRI is an ISDN user–network interface composed of two B-channels and one D-channel $(2B + D)$. The B-channel is a 64 kbps channel intended to carry voice or nonvoice user information streams. Minimum bit alteration (bit integrity across the PACS air interface) could be guaranteed by using specific error-correction protocols.

The D-channel is a 16-kbps channel that carries signaling and control information on the network side under LAP-D link-layer protocol.

PACS can provide B-only, D-only, B+D, or 2B+D circuit-switched bearer capabilities to support wireless extensions of the ISDN capabilities. The data signaling rates for BRI support up to 144 kbps. The number of BRI interfaces provided in PACS is limited by the capability of the existing air interface of 256 kbps. The higher rates are provided at the air interface by the aggregation of two or more slots.

The service provider may offer one 64-kbps B-channel for dialed digital data and/or for voice services. With a dialed 64-kbps data circuit, the WAFU provides the user with a serial data port interface that uses a standard modem dialing command set, such as AT-602 AT command standard. In this manner, the computer equipment operates as if it is connected on a serial port to a standard modem even though in reality it is connected to the PACS system. In this mode of operation, no modifications to the computer's communications software configuration is required.

c) Leased digital data service: The PACS subscriber can obtain full-period data circuits at the following rates: 32, 48, 64, 128 and 256 kbps. In addition, PACS can carry 14.4 over a 16-kbps air interface channel and pack it into an ISDN B-channel at the switch interface using the standard ISDN rate adaptation schemes. This conserves bandwidth on the wireless link while maintaining compatibility with the ISDN bearer channel types.

2) Messaging Services: PACS provides the following point-to-point message services.

- One-way and unacknowledged, mobile terminated, short message service of up to 256 characters.
- Two-way acknowledged message service for both mobile originated and terminated messages of up to 4 kbytes of text.
- An extended messaging service that permits files of up to 16 Mbytes for both mobile originated and terminated file transfer. The applications for this messaging service include text messages, e-mail, and fax imaging, as well as graphics imaging, PCM and ADPCM encoded sound, Moving Picture Experts Group video, and more.

3) Packet Mode Data Services: The packet mode data service is a shared, contention-based, RF packet protocol using a data sense multiple access contention mechanism [19]. The downlink uses near perfect scheduling. The basic structure of the PACS packet channel (PPC) allows operation of subscriber units that are capable of operating on a single time slot per TDMA frame as well as subscriber units that achieve higher throughput and lower packet delays by using multiple time slots per frame. The protocol allows both types of subscriber units to share the available packet bandwidth in a fair and equitable manner. PPC provides the user with a variable-bandwidth, asynchronous, asymmetrical data service at gross data rates up to 256 kb/s. PPC supports dynamic sharing of bandwidth with the PACS circuit mode services (speech, circuit mode data, etc.), allowing PPC to use the bandwidth otherwise idle. User authentication, data privacy, mobility management, and user anonymity features are provided using signaling procedures very similar to and compatible with the circuit-mode security procedures. All PPC signaling, however, takes place over the PPC channel rather than using circuit-oriented call control.

The high data rate and variable-bandwidth nature of PPC is well suited to the carrying of local-area-network-oriented computer network data traffic. Wireless Internet access, mobile computing, etc. are applications that are suitable over the PACS packet channel.

4) Interleaved Speech/Data: The interleaved speech/data service provides the ability to transmit both speech information and data information by using a single 32-kb/s time slot. Data is transmitted during the quiet times between speech bursts. Data bursts are reliably delivered by the LAPR protocol and, as with all PACS data services, are enciphered for privacy.

C. Basic and Supplementary Services

PACS provides all the basic telephony services (e.g., call origination, call delivery, call clearing, emergency call, etc.) and a rich set of supplementary services (call waiting, call forwarding, three-way calling, calling number/name delivery, etc.). When used for WLL service, and when the features are derived from the switch, all the features supported by the switch (e.g., custom calling features, centrex features, etc.) are also available to the subscriber.

V. WAFU Functions and Maintenance Features

A WAFU provides the necessary interworking between the operation of conventional telephone equipment and the PACS air interface protocols. A WAFU appears like a portable SU to the rest of the PACS network. Therefore, it follows the PACS air interface specifications for layers 1, 2, and 3. In addition, a WAFU provides a two-wire analog interface to the customer premises equipment.

A. WAFU Functions

In general, the interface supported by the WAFU to the customer premises is similar to the subscriber loop interface supported by a local switching system. However, the WAFU supports a relatively short loop between the WAFU and the attached analog phones that are confined within the customer's residence or business. The WAFU is expected to meet the requirements for supporting single-party loop lines. Following is a sample of functions provided by the WAFU over the T-interface.

- Provide a two-wire tip-ring interface to conventional analog telephone equipment. The wiring used may be the existing two-wire copper pair that was previously used for conventional analog phones.
- Provide all physical layer functions to the subscriber: battery, overvoltage, signaling, hybrid, ringing, and test.
- Support customer lines signaling from the analog telephones. They include detection of off-hook and on-hook and other supervisory states like idle state, flash hook, alerting state, etc.
- Be able to detect dual tone multifrequency signaling and dial pulse signaling.
- Pass all call progress signals and busy or inoperable radio link conditions.
- Provide line powering, including backup powering, to continue operation in case of power failure.
- Control the loop/ground start circuit.
- Detect 911 calls and voiceband modem signals.
- Provide howler tone for receivers left off-hook after call termination.
- Support "on-hook data transmission associated with ringing" for the calling party number/name information and "on-hook data transmission not associated with ringing" for short messaging.

The WAFU may be implemented with additional digital line interfaces. The standard digital interface may be a 9-pin connector for a serial data port that uses TIA-232-E electrical interface and the AT-602 modem protocol or a RJ-45 connector for a 10 Base-T Ethernet port.

B. WAFU Maintenance Features

Alarm and diagnostics features are built into the PACS system to reduce the operating cost of WLL installations. When the WAFU's detect a failure condition, an alarm is activated. When an alarm occurs and when an alarm condition is cleared, the WAFU sends the network-specified alarm messages that identify the type and severity of the alarm. The types of alarms included are power supply failure, power supply—low condition, antenna failure, system failures, temperature out of range, etc. The severity of the alarms can be classified as cleared, minor, major, or critical.

Diagnostics features included in PACS to allow the operator to verify the operation of the WAFU's are as follows.

- *Analog loopback:* the RPCU generates a tone that the WAFU receives, passes through its vocoder, and loops back to the RPCU.
- *Digital loopback:* the RPCU sends a digital pattern that the WAFU demodulates and sends back to the RPCU.
- *Tip and ring testing:* the RPCU commands a series of tests to check tip-to-ground, ring-to-ground, and tip-to-ring short circuits. The equipment for these tests is part of the WAFU.

VI. Summary

PACS has been engineered for wireline quality voice service, a wide range of data services, and low costs. Its low complexity and low power yield moderate cell sizes, which make it an excellent choice for urban and suburban applications where user density and traffic demand are high. PACS is the end product of years of research and development at Bellcore, coupled with research, development, and lessons learned in the TDMA-based Japanese personal handy phone system, months of review under the auspices of the ANSI standardization process, and product development experience by some of the leading manufactures in the telecommunications industry.

References

[1] D. C. Cox, "Wireless network access for personal communications," *IEEE Commun. Mag.*, vol. 30, pp. 96–115, Dec. 1992.

[2] ——, "A radio system proposal for widespread low-power tetherless communications," *IEEE Trans. Commun.*, vol. 39, pp. 324–335, Feb. 1991.

[3] A. R. Noerpel, Y.-B. Lin, and H. Sherry, "PACS: Personal access communications system—A tutorial," *IEEE Personal Commun. Mag.*, pp. 32–43, June 1996.

[4] *Personal Access Communications Systems Air Interface Standard*, ANSI J-STD-014, June 1995.

[5] *Personal Access Communications Systems Unlicensed (version B) Air Interface Standard*, ANSI J-STD-014B, Sept. 1995.

[6] "Mobility management application protocol (MMAP)," ANSI T1-651- 1996, 1996.

[7] "Mobility management application protocol (MMAP) RCF-RACF operations," ANSI T1-659-1996, 1996.

[8] "Cellular radio telecommunications intersystem operations," IS-41 TIA/EIA IS-41 C, 1996.

[9] V. K. Varma, N. R. Sollenberger, L. F. Chang, and H. W. Arnold, "A flexible low-delay TDMA structure," in *Proc. IEEE ICC'91*, Denver, CO, 1991, pp. 1474–1479.

[10] J. C. I. Chuang, "Autonomous adaptive frequency assignment of TDMA portable radio systems," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 627–635, Aug. 1991.
[11] V. Varma, A. R. Noerpel, and D. J. Harasty, "Integrated alerting and system broadcast channel for a wireless access system," *IEEE Trans. Veh. Technol.*, vol. 45, pp. 157–163, Feb. 1996.
[12] D. Brown, "Techniques for privacy and authentication in personal communications systems," *IEEE Personal Commun. Mag.*, pp. 6–10, Aug. 1995.
[13] "Integrated digital loop carrier system generic requirements, objectives, and interface," Bellcore GR-303-CORE, issue 1, Sept. 1995.
[14] "Switching and signaling generic requirements for network access services to personal communications services (PCS) providers," Bellcore GR-2801-CORE, issue 1, Dec. 1993.
[15] A. R. Norepel, P. Lukander, L. F. Chang, V. K. Varma, and E. H. Lipper, "Supporting PACS on a GSM MSC," *IEEE Commun. Mag.*, pp. 114–123, Sept. 1996.
[16] "40, 32, 24, 16 kb/s adaptive differential pulse code modulation (ADPCM)," International Telecommunications Union, Geneva, Switzerland, ITU-T Recommendation G.726, Dec. 1990.
[17] "Coding of speech at 16 kbps using low delay code excited linear prediction," International Telecommunications Union, Geneva, Switzerland, ITU-T Recommendation G.728, Sept. 1992.
[18] L. F. Chang, D. J. Harasty, and A. R. Noerpel, "Circuit based data transport for a wireless access communications system," in *Proc. IEEE ICUPC'93*, Ottawa, Canada, 1993, pp. 754–758.
[19] J. C. Smolinske, P. M. Tran, C. L. Clanton, and R. C. Scheibel, Jr., "A 512 kbps high capacity packet mode data protocol for the broadband PCS spectrum," in *Proc. IEEE VTC'96*, Atlanta, GA, 1996, pp. 536–541.

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