

Abstract

The SWAP specification for wireless voice and data networking within the home will enable a new class of mobile consumer devices that draw from the power and content of the Internet and the home PC. If cable modems and xDSL represent the "last mile" access to the home, then HomeRF™'s mission with SWAP could be called the "very last 150 feet" within and around the home. HomeRF has the broad backing of the major corporate stakeholders for networking within the home and is optimized specifically for the cost/performance point needed for consumers. The technology leverages the existing PC-industry infrastructure around the Internet, TCP/IP, and Ethernet, and adds a standard way to connect to the PSTN for voice telephony. First products should appear in late 1999, and future versions with enhanced features and/or higher data rates should follow in one to two years.

HomeRF: Wireless Networking for the Connected Home

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Two major factors are presenting a real opportunity at last for data networking within the home. The first is the explosive growth and usage of the Internet. The Internet clearly has the potential to revolutionize the delivery of information and entertainment to the home. The second factor is the emergence of sub-\$1000 powerful home PCs. With these low-cost devices the barrier to getting on the Internet and discovering the utility of the PC is low enough to reach the vast majority of middle-income households.

However, consumers soon find that the PC/Internet combination, although very compelling, lacks some key attributes in terms of mobility and convenience of location compared with many of their traditional information and entertainment options such as newspapers, magazines, TV, videos, FM radio, CD/stereo, and so on. The powerful home PCs (and the printers and peripherals attached to them) often end up turned off 20–22 hours a day while tucked into a bedroom or den corner where access is possible only within a 2–3 ft "bubble." The major opportunity for networking in the home is thus to extend the reach of the PC and Internet throughout the home and yard, and connect the resources of the PC and Internet with legacy home applications such as telephony, audio entertainment, and home control systems. Another opportunity is the sharing of resources (such as an Internet gateway or high-quality printer) among PCs in multi-PC homes.

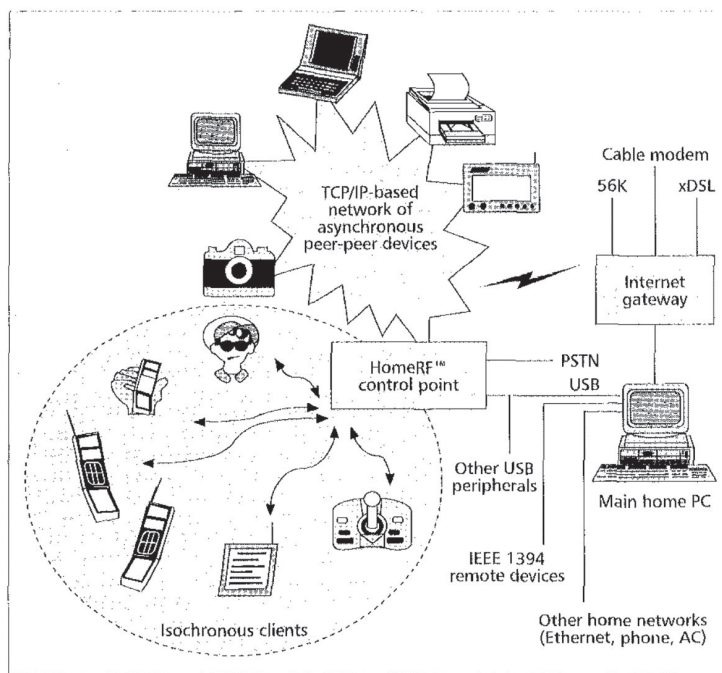
With these issues in mind, several major stakeholders in the home PC industry formed the Home RF Working Group (or "HomeRF") in early 1997. The key goal of the group was and remains to enable interoperable wireless voice and data networking within the home at consumer price points. HomeRF started by pooling market research from the member companies to produce a Market Requirements Document. This document guided the technical proposals within the group, and with tremendous cooperation from major stakeholders in the RF communications industry and the nascent wireless LAN community, the Shared Wireless Access Protocol (SWAP) was created. HomeRF is now in the process of bringing the SWAP specification to its final released form.

This is proceeding very quickly due to the native support within SWAP for TCP/IP networking and Internet access, and for voice telephony via the public switched telephone network (PSTN), or voice over IP. SWAP achieved support for these important network stacks easily by reusing major sections of proven RF protocols and then simplifying them where appropriate for home usage.

Today the HomeRF organization consists of approximately 100 members representing the bulk of the PC, telecommunications, and consumer electronics industries. General information on the organization is available at <http://www.homeRF.org>. The specification described in this article started at Revision 0.1 from a proposal made in late 1997, and was approved and published as Revision 1.0 in January 1999. As of this writing, the Revision 1.2 specification is available, which includes methods of bridging between a HomeRF network and wired networks such as Home Phoneline Networking Alliance (HomePNA) and Ethernet.

Vision and Applications

HomeRF sees SWAP as one of several connectivity options for the home of the future. The relationship of SWAP with other connection options is shown in Fig. 1. In this scenario, the main home PC is linked somehow to an Internet gateway that might be a 56K, digital subscriber line (xDSL), or cable modem. This link may be a simple cable, a wired network connection, or even a SWAP network connection. This main home PC would likely have a variety of built-in or peripheral resources such as a printer, a scanner, a CD drive, a DVD drive, and so forth. For most home PCs today and looking forward, USB would be the bus of choice for many peripherals that do not need to be mobile or remote from the home PC. For video applications such as connecting camcorders, IEEE1394 is the expected choice, and there are no viable RF alternatives at consumer price points at this time (although VVIR at 16 Mb/s is a reasonable "no-cable" choice). HomeRF also expects that other networking choices will also be viable for sharing resources among multiple PCs, as shown in Fig. 1. These options include conven-



■ Figure 1. The SWAP vision for home networking.

tional 10/100BaseT Ethernet, home phone line Ethernet, and AC power line networking. The last option is particularly well suited for many home automation scenarios where very low data rates are acceptable.

The SWAP networking vision is also apparent in Fig. 1. The HomeRF technology supports both isochronous clients that are slaves to the main home PC and an asynchronous network of peer devices which is effectively a wireless Ethernet. In most cases the system starts with a control point, usually connected to the main home PC via USB. This control point is not absolutely necessary for devices in the asynchronous network of Fig. 1, but even in that case it offers some interesting power saving options for ultra-portable devices, as will be described in the medium access control (MAC) overview later. The isochronous clients, such as cordless telephones, wireless headsets, or remote I/O devices to the home PC (a consumer personal information manager, PIM), are always bound to the control point, which assigns them guaranteed bandwidth for bounded latency communication. The asynchronous peers can also communicate to the main home PC as with any other peer device. Note that data transfer on the asynchronous network between any two peers is directly to each other as opposed to routed through the control point. Consider now three major applications for the HomeRF technology.

The first example is PC-enhanced cordless telephony. Today there are no standards-based digital cordless telephones for consumer use in the United States where interoperability of multiple vendors is enabled. HomeRF defines a new standard for interoperable digital cordless telephones both in the United States and globally. Furthermore, the SWAP specification includes a standard method for connecting the cordless telephone to the home PC software applications. Thus, many new enhanced features are possible. For example, caller ID information could be sent to a PC application to look up the caller's name and then route the call to an individual handset (rather than number) and display the

caller's name on any given handset. For outbound calls, the PC could interpret a spoken destination name (i.e., "Call Mom") through voice recognition, and then based on date/time determine the likely number for the person and route the call using the lowest-cost approach (which might be IP telephony). The handset could be used to pick up voice mail selected by the user from the home PC call center. With voice synthesis the handset could also be used to "listen" to e-mail. With more sophisticated application software, the handset could achieve PIM functionality by using voice or keypad I/O to store lists (i.e., "Add 3 quarts of milk to my shopping list") or control home automation features (i.e., "Turn the temperature up 3 degrees"). All of these and undoubtedly much more creative features are possible because of the standard interoperable method of connecting to the home PC. The cordless handsets themselves are slightly different, but not substantially more complex or expensive, than the existing "dumb" cordless handsets sold in multimillion unit volume today.

A second interesting example is a mobile viewer appliance. This could take many forms, but fundamentally consists of a color LCD display (like that of a notebook computer) with some limited input device (e.g., a pen) and a SWAP radio network connection. Such a device could be either an extension of the home PC (like an X-terminal) or simply a Web browsing extension of an Internet gateway. In either case the viewer communicates entirely through receiving and sending TCP/IP packets.

The third of many potential applications is resource sharing among multiple PCs in the same home. The resource to be shared could be a high-quality printer, a backup storage device, or an Internet connection. Another possibility for this is multiplayer gaming. Clearly these resource-sharing applications have received considerable attention from other home-wiring-based alternatives to networking. It is important to note that the market for HomeRF is not strictly multi-PC homes. Any home with a modern home PC or an Internet gateway is a candidate for compelling portable devices enabled by the SWAP specification.

Network Topology

The SWAP architecture is a unique combination of a managed network that provides isochronous services such as interactive voice, and an ad hoc peer-to-peer network that provides traditional data networking. The protocol has been optimized to provide the kinds of services most needed from untethered devices in the home. Three kinds of devices can be in a SWAP network:

- A connection point (CP), which acts as the gateway between the personal computer, PSTN, and SWAP-compatible devices
- Voice devices (isochronous data devices, also called I-nodes)
- Asynchronous data devices, also called A-nodes

The control point is usually connected to the main home

PC, typically via USB. It may also have a connection to the PSTN. It is capable of performing data transfers to and from other data devices using an asynchronous contention-based protocol. The control point manages the network to provide priority access to the radio medium for isochronous devices.

Thus, the SWAP protocol is a hybrid in several ways; it is client-server between the control point and voice devices, but peer-to-peer between data devices. The interactive voice transactions are circuit-switched, time-division multiple access (TDMA), but the asynchronous transactions are packet-switched, carrier sense multiple access (CSMA). It is precisely this richness that gives SWAP the capability to be broadly used in the home; it is not designed to support hundreds of users doing similar things in an enterprise, but rather the variety of applications that occur in a residential setting. There are several usage scenarios the SWAP protocol was designed to support; these focus on the exchange of voice and data by portable devices within the home environment. Typical uses the network was designed to support include:

- *A busy family*

- Three children play interactive PC games with each other from their rooms. They can talk to each other through their PCs.
- Mom is in the kitchen listening to her phone messages recorded by the PC answering machine application.
- Dad is in the garage completing an oil change. He enters the data into the car maintenance log he maintains on his PC into the display pad.

- *A montage of voice applications*

- Mom is using her personal handset to record a message for the kids to listen to when they return from school.
- Dad is asking for stock quotes from the Internet and getting a vocalized response through a text to speech (TTS) engine.

- Dad checks the temperature in the garage and turns on a space heater via voice commands.

- Uncle Ed listens to a soccer match broadcast via audio over the Web to his wireless headset on the front porch.

- *A montage of display applications*

- Mom pulls up a recipe from the PC and adds oregano to the shopping list.

- Dad updates the family financial portfolio.

- Junior plays Tetris.

- Daughter reads the latest online issue of *Teen* magazine.

Figure 2 shows an example of a typical SWAP network consisting of two A-nodes, one I-node, and a CP. One of the A-nodes is a power managed display pad whose communications traffic is managed by the PC so that it can maximize battery life. Although not shown in this figure, the laptop A-node could also be power managed. As this figure shows, SWAP has a unique ability among networking protocols to mix intense, high-demand packet traffic with infrequent command and control traffic and with high-quality voice traffic. The personal computer is an integral part of the SWAP system, although peer-to-peer data networking is available even when the PC is inoperative.

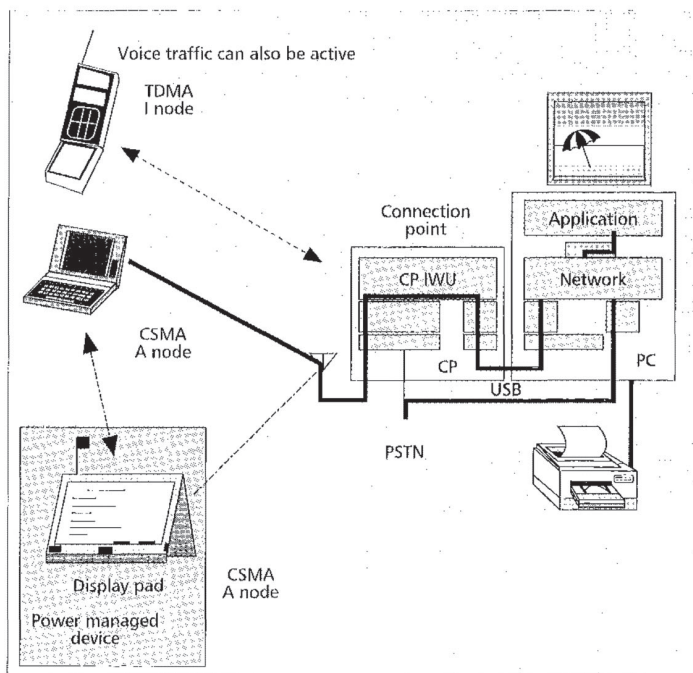
Software Architecture for the PC

SWAP asynchronous data devices will be supported in Microsoft Windows via the NDIS driver library. The NDIS library performs many of the functions common to all networking device drivers, such as synchronization, and also provides a standard interface for higher-level applications to access. Manufacturers of network adapters are only required to produce a miniport driver that provides functionality specific to their hardware. Miniports of a given media type can be used with higher-level protocols knowledgeable about that media type with no further modifications, as shown in Fig. 3, where the shaded blocks are provided by the operating system.

Hardware manufacturers producing A-node devices should write a connectionless miniport that declares itself a member of the Ethernet media type. To higher-level protocols, SWAP A-nodes will be indistinguishable from regular Ethernet adapters, allowing Ethernet-knowledgeable applications to immediately function with SWAP devices.

Hardware manufacturers producing isochronous CP devices should write a device driver that provides a TAPI interface. TAPI is a simple, generic set of objects, interfaces, and methods for establishing connections between devices; TAPI communicates with the CP via a TAPI service provider. TAPI applications will be able to set up, control, and take down calls on SWAP devices via the TAPI interface (Table 1).

Some device designers may wish to stream voice conversations between the SWAP adapter and another adapter within the PC in real time. An example scenario would be that of a voice conversation between the SWAP adapter (i.e., a user with a SWAP handset communicating with the SWAP adapter) and another adapter in the PC (e.g., a modem attached to a phone line or a sound card attached to speakers and a microphone). In Windows 2000 and



■ Figure 2. SWAP network topology flexibility.

98, voice data can be streamed between adapters via the DirectShow streaming architecture. A DirectShow filter graph is plumbed from the data source (in this case, the SWAP adapter) to the data sink (the modem or sound card). The Media Service Provider (MSP) interface provided by TAPI 3.0 enables the application to control and access the Direct Show voice data stream.

The MAC Overview

The SWAP MAC has been optimized for the home environment and is designed to carry both voice and data traffic and interoperate with the PSTN using a subset of the Digital Enhanced Cordless Telecommunications (DECT) standard, a digital cordless telephone standard used in residential applications throughout Europe. The MAC is designed for use with a frequency-hopping radio and includes a TDMA service to support the delivery of isochronous data (e.g. interactive voice), and a CSMA with collision avoidance (CSMA/CA) service derived from wireless LAN standards such as IEEE 802.11 and OpenAir to support the delivery of asynchronous data. The SWAP MAC provides the following features:

- Good support for voice and data by using both TDMA and CSMA/CA access mechanisms

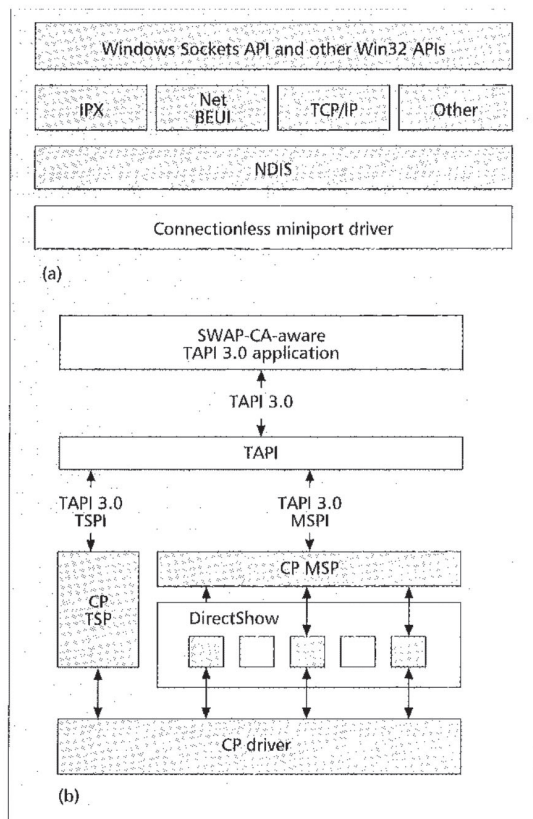


Figure 3. a) SWAP A-node driver architecture; b) SWAP I-node driver architecture.

OS	A-node	I-node
Windows 95	Connectionless miniport	Call control only through TAPI 2
Windows NT 4	Connectionless miniport	Call control only through TAPI 2
Windows 98	Connectionless miniport	TAPI 3.0 call control DirectShow access to voice stream TAPI 3.0 MSP control of voice stream
Windows NT 5	Connectionless miniport	TAPI 3.0 call control DirectShow access to voice stream TAPI 3.0 MSP control of voice stream

Table 1. SWAP driver architectures for recent Microsoft operating systems.

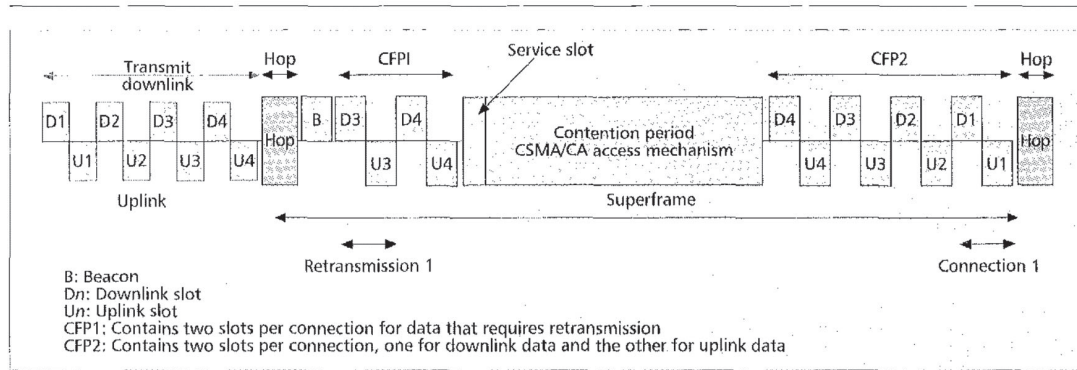
- Support for four high-quality voice connections with 32 kb/s adaptive differential pulse code modulation (ADPCM)
- High data throughput of 1.6 Mb/s
- Data security — None/basic/robust levels of encryption
- Power management for both isochronous and asynchronous nodes
- 24-bit network ID

The MAC protocol uses a superframe as illustrated in Fig. 4, which incorporates two contention-free periods (CFPs) and a contention period. The start of the superframe is the point at which a station begins to hop to a new channel and ends immediately before the station starts to hop to the next channel. The duration of the superframe is fixed and is the same as the dwell or hop period. The access mechanism used during each CFP is TDMA, while the access mechanism used during the contention period is CSMA/CA.

Each CFP is divided into a number of pairs of fixed-length slots, two per voice connection. The first slot in each pair is used to transmit voice data from the CP to a node (downlink), and the second is used to transmit voice data from a node to the CP (uplink). In a managed network a beacon is transmitted immediately after the hop. This beacon is used to maintain network synchronization, control the format of the superframe, and manage when each node should transmit and receive data.

CFP2 at the end of the superframe is used for the initial transmission of the voice data, while CFP1 at the start of the superframe is used for the optional retransmission of any data which was not received or incorrectly received in the previous dwell. The dwell period is fixed at 20 ms to provide acceptable performance with respect to latency. The length of the dwell period also means that each voice data message contains 20 ms of ADPCM data (640 bits), equivalent to an extended DECT B-field, and 56 bits of control data, equivalent to the DECT A-field plus some additional addressing information. With a 20 ms superframe the MAC can provide four voice connections with a large enough CFP at the start of the frame to enable up to four retransmissions to be accommodated.

CFP2, in which initial transmission occurs, and CFP1, in which retransmission occurs, are separated by a frequency hop, giving frequency and time diversity, which is particularly important given the potentially noisy environment in which the protocol operates. At the end of CFP1 in the superframe there is a space reserved for a service slot which is used by voice nodes to request connections from the CP. Each voice data packet transmitted by a node includes in the packet header a piggyback acknowledgment of the last voice data message received by the node. That is, in the uplink packet, the voice node acknowledges the downlink packet sent by the CP. This system allows the CP to determine prior to a hop which voice data transmissions were lost, determine the retransmissions required, and advertise these retransmissions



■ Figure 4. A SWAP frame description.

in the beacon at the start of the next superframe; each voice data packet can only be retransmitted once.

For data traffic a CSMA/CA access mechanism is used during the contention period of the superframe. With this scheme, the protocol provides efficient data bandwidth even with concurrent active voice calls and microwave oven interference. Peak effective user throughputs of over 1 Mb/s are possible under lightly loaded conditions in the 1.6 Mb/s 4-frequency shift keying (FSK) mode. Furthermore, data transfer rates of hundreds of kilobits per second can occur even with four voice calls active simultaneously.

The CSMA/CA mechanism is similar to Ethernet (802.3), enabling easy integration with an existing TCP/IP protocol stack within a host platform; the main difference with Ethernet is the slotted contention mechanism and the addition of MAC-level acknowledgment of unicast packets. Figure 5 illustrates how the medium is accessed during the contention period.

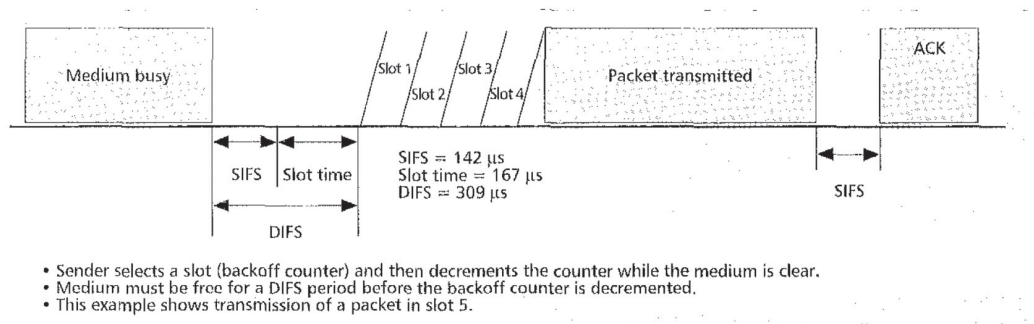
The CSMA/CA access procedure is designed to provide fair access to the medium to all nodes by using a contention window and backoff counter, as shown in Fig. 4. Before any node transmits a packet it selects a backoff counter (a number of contention slots) and then starts listening. When the medium has been clear for a DIFS period it decrements its backoff counter for each free contention slot. When the backoff counter expires the node transmits the message. Whenever the medium is busy the countdown is suspended and only resumes when the medium has been free for a DIFS. This backoff mechanism reduces the probability of collision, and performing a backoff before transmission also ensures that responses from multiple nodes responding to a broadcast message on an otherwise idle network do not all collide. If a retransmission is required because of a collision or transmis-

sion failure, the size of the collision window is increased from an initial value of 8 exponentially up to a maximum 64 to avoid congestion.

If there is no CP present, the data nodes can create an ad hoc network in which control of the network is distributed between all the nodes. The primary function of the beacon is to enable all nodes to synchronize to the hopping pattern of the network. The beacon transmitted by the CP is also used to manage the network during the CFPs. The CP beacon (CPB) can include a list of active voice connections (and therefore slot assignments), retransmission slot assignments for the current superframe, connection status information, and paging information. The CPB can also provide power management for isochronous and asynchronous nodes to maximize the battery life of portable devices.

The procedure for power management of isochronous nodes is straightforward. In this process, during an active connection (e.g., a voice call) the isochronous nodes power on, initially only for the duration of the CPB, to receive slot assignment information. They then power down until their assigned slots are due. When not in an active connection state, isochronous nodes need only power-up every N dwells, where N is chosen by the system designer according to the application being supported, and as a compromise between power-saving and speed of response to a new connection.

The CP also provides power management services for asynchronous nodes. Figure 6 illustrates the process for sending broadcast messages to power-saving asynchronous nodes (PS-nodes), which is described as follows. The CP maintains a countdown to the next dwell when PS-nodes should wake up, which is broadcast in the CPB. In step 1, PS-node 3 powers up and receives the "dwells-to-broadcast"



■ Figure 5. The CSMA medium access procedure.

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