High Speed Home Networking for AV and IP Applications using existing Powerline Infrastructure

既存の電力線を利用した AV 及び IP アプリケーションのための高速ホームネットワーク

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Abstract

Sharp, in collaboration with a partner**, has developed a novel system for networking inside homes using existing powerlines. This technology provides over 175 Mbps PHY data rate, with advanced QoS support, for AV (HDTV, SDTV, audio and AV/C) and IP applications (browsing, streaming). The system, described in this paper, incorporates innovative concepts at different protocol layers: A filtered OFDM PHY technology for robust, high speed data transport over the powerline channel, an OFDMA MAC protocol combining contention and contention free protocols, and ad-hoc network management concepts including hidden node support, multiple network coordination, topology discovery etc. The superior coverage and capacity performance of the PHY and the OFDMA MAC, evaluated through field-testing of a prototype implementation, are also described. Parts of this system may be adopted by the HomePlug AV standard and enter products in 2005-6.

** Conexant Systems

シャープは，他社[注]と共同して，既存の電力線を利用する家庭内での新ネットワークシステムを開発した。この技術は，AV（HDTV，SDTV，オーディオ，及びAV/C）製品とIPアプリケーション（ブラウジング，ストリーミング）に，先端的QoSサポートとともに175Mbps以上のスピードを提供する。本稿で記述しているこのシステムは，異なったプロトコルレイヤにおける，革新的概念が組み込まれている。即ち，電力線チャネル上における頑強な高速データ送信のためのフィルタをかけたOFDM PHY技術，コンテンションとコンテンションなしのプロトコルを組み合わせたOFDMA MACプロトコル，および，隠れノードサポート，複数ネットワーク連携，トポロジー発見等を含むアドホックネットワーク マネジメント コンセプトである。プロトタイプ実装のフィールドテストで評価されたPHYおよびOFDMA MACの優れた通信範囲や通信容量に関する能力も，説明している。このシステムをHomePlugのAV標準に提案している。HomePlugのAV標準化が実現すれば，2005－2006年に製品導入する会社が出てくると考える。

注：Conexantシステム社

Introduction

In-home networking of CE devices is a theme that is currently drawing tremendous interest from communications and CE companies. This shift in focus from the access segment into the home has been facilitated, in part, by the phenomenal success of 802.11 WLANs and the growth of end-user applications. As the applications within the home grow in both their BW requirements as well as Quality of Service (QoS) needs, networking technologies are developing apace to support them. Sharp Laboratories of America (SLA) and Conexant Systems anticipated this confluence of the traditional Consumer Electronics and Networking industries and designed and developed a high performance power-line communications (PLC-AV) solution.

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The use of medium and low voltage power lines for data communications has been studied for more than 15 years. The HomePlug (HP) 1.0 technology [1] supports networking with rates up to 14 Mbps in the sub 30 MHz spectrum band. HP 1.0 products are primarily used for data networking (IP based web browsing etc.) inside the home or small office. HP 1.0 and other powerline technologies are also being deployed for last-mile access over low-medium voltage powerlines by electric power utilities. This initiative, called Broadband over Powerline (BPL) and the issues involved in BPL, are beyond the scope of this paper. This paper addresses the features of a powerline communications (PLC-AV) system designed to support much higher data rates than HP 1.0, and QoS for AV applications within the home, though this technology can also be used for BPL applications.

The prevalence of power outlets in every room, an existing power-line grid covering the entire home, and the need to plug most AV CE equipment into a power outlet, make PLC-AV a natural choice for home networking. **Fig. 1** shows typical usage scenarios for the PLC-AV technology. The PLC-AV system, described in this paper, supports the communication requirements of existing and emerging AV devices such as HD recorders, PVRs, HDTV capable LCD TVs, audio systems, PCs and PC peripherals. This system also facilitates the development of new applications that exploit the capabilities of data sources like PCs, set-top boxes and AV sources and renderers like LCD TVs and high performance speakers.

The value proposition of this system has many dimensions that distinguish it from other home networking solutions:

- PLC-AV is designed primarily to support AV distribution within the home. This includes multiple simultaneous HDTV and/or SDTV streams, audio, and streaming AV over IP content.
- PLC-AV provides improved coverage that is better than the coverage in WLANs. Variable and spotty coverage is widely recognized as one of the limitations of wireless solutions. The capacity provided is also higher than current WLANs.
- The PLC-AV network can serve as a high-speed backbone within the home, supporting WLAN and UWB hubs that extend coverage as well as provide wire-free connectivity.
- AV equipment and PCs and peripherals no longer have to be placed in central locations around a TV or PC. De-centralized entertainment center or PCs give the user great flexibility in the layout of his living space.
- This technology can significantly reduce or remove the nest of wires around PCs or entertainment centers.
- PLC-AV also provides mobility/portability like wireless (user can move portable LCD-TVs from one outlet to another) while connecting to remotely located DVD players and set-top boxes.
- PLC-AV enhances the user experience by allowing TVs in multiple rooms access HDTV or other content from different sources (set-top box, DVD players, PCs etc.)
- Finally, the PLC-AV system is a secure technology. Besides the encryption and key management capabilities, it is hard to physically tap into a home powerline network, unlike wireless.

The salient features of the different protocol layers in the PLC-AV system are summarized in the following sections. Further details may be obtained from [3].

1. Network architecture

Fig. 2 shows the organization of PLC-AV devices into different classes of networks. The main PLC-AV network in a home, called Central Network (CN) here, is designed

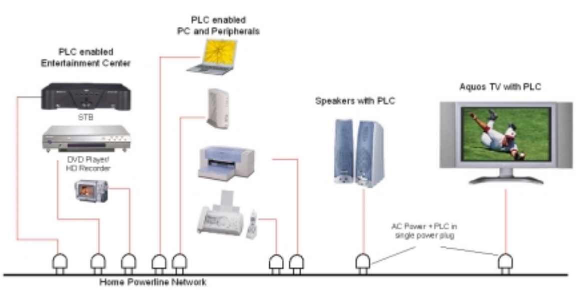

Fig. 1　In-Home Application Scenarios for Power-line Networks.

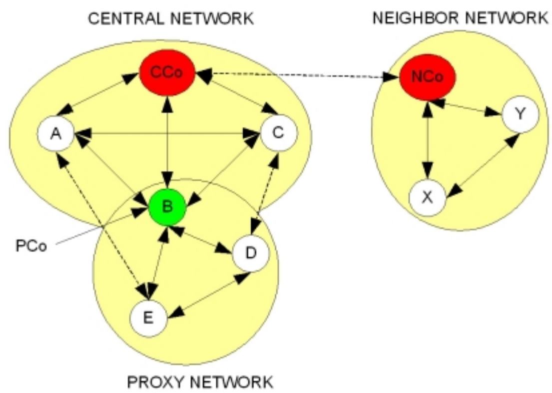

Fig. 2　PLC-AV Network Architecture.

to support peer to peer communications between devices in the network, while the network is managed by a single controlling entity called the Central Coordinator (CCo). The CCo does not act as a data relay, but performs network critical functions such as bandwidth allocation and security (key management, authentication, etc.).

The powerline medium is described in greater detail in Section 2. Access to the powerline medium is shared by multiple PLC-AV devices, which could interfere with one another, even if they belong to different logical associations or networks. Networks may overlap in terms of interference between devices, but the authentication and association processes and use of different network encryption keys isolate their operations. The interference environment, coupled with the peculiar nature of the powerline channel, gives rise to situations where certain devices that belong to the same home network may not be able to communicate with the CCo. A Proxy Network (PN) is instantiated in such scenarios to allow control of the "hidden devices" through a relay of communications between a Proxy Coordinator and a CCo. Direct peer-peer communications are still enabled between devices in a PN and devices in the CN with which the PN is associated. The PN concept improves coverage by enabling communications for hidden devices (HDEVs).

While PNs are always dependent and associated with a CN, a Neighbor Network is an entirely autonomous association of PLC-AV devices. Neighbor networks are independent networks that can exist in the same home (multiple instantiations of the CN) or in neighboring homes. Without the use of filters, RF isolation between neighboring networks is not possible. In such scenarios, the Coordinators of Neighboring Networks coordinate the sharing of BW, so that access to the medium is shared fairly by the various networks and QoS is preserved for communications within a network.

2. Spectrum, powerline channel and interference

The spectrum available for use in home PLC-AV networks varies across geographical areas. Regulatory bodies in Europe, Japan and the US have adopted different spectrum policies. In the US, the FCC restricts radiation emissions above 30 MHz to levels at least 30 db less than emissions below 30 MHz. The HAM bands below 1.705 MHz have similar tight emissions restrictions, providing a usable spectrum range from 2-30 MHz. Numerous HAM bands are also interspersed in that range. This PLC-AV system uses the 4-28 MHz frequency range while meeting out of band emissions regulations for the in-lying HAM bands.

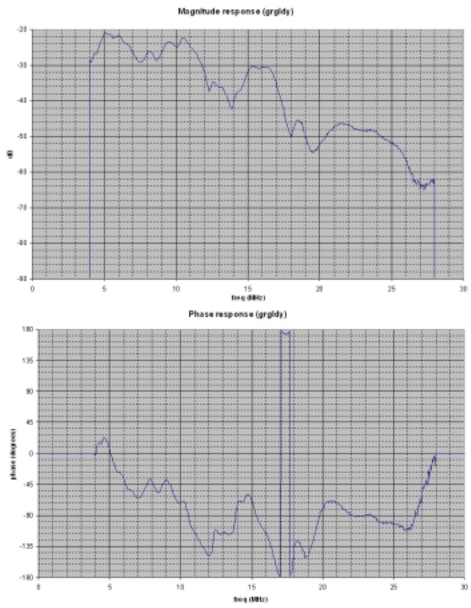

Fig. 3 Amplitude and Phase Response of typical powerline channel.

The powerline channel is a very challenging environment for reliable, high BW communications. The channel transfer function shows frequency selective nulls that change with time and the transfer functions between different outlet pairs are unique and directional. The channel also exhibits significant attenuation (35 db+) and group delay variation across the passband. Furthermore, the transfer function can change significantly as appliances are plugged in or out and turned on/off, as the load impedance presented by the appliance changes. The amplitude and phase responses for a typical powerline channel are shown in **Fig. 3**.

The chief limiting factor for the performance of the PLC-AV system is interference. In the powerline environment, interferers can be impulsive, broadband or frequency selective. Examples of sources of interference are dimmers, phone chargers, halogen lamps, switching power supplies in appliances, brush motors etc. The behavior of these interferers varies widely and is hard to model. Two typical impairments are: a.) abrupt impedance change (3 - 20dB), which is locked to the AC power cycle from devices like phone charger, and b.) impulse noise, which generally is periodic (20 - 200 kHz) from devices such as dimmer switches.

The effect of interference, coupled with the channel transfer function, makes the capacity between outlet pairs vary significantly. Therefore, in addition to the challenge of enabling high data rates in excess of 150 Mbps, improving capacity between poor outlet pairs or the overall coverage is a design imperative that is also addressed by the PLC-AV PHY and MAC described below.

3. OFDM PHY/MODEM

The PLC-AV system PHY is based on filtered Multi-Carrier (OFDM) modulation that allows it to support both Frequency and Time division multiple access (OFDMA). Among current and emerging networking standards, this feature makes the PLC-AV PHY very powerful and unique, and delivers significant capacity improvement.

The frequency of tone k is k* 39.0625 kHz. The Base Tone Set is defined by k from 103 to 716 inclusive (covering 4-28 MHz). A Tone Mask is a subset of tones from the base tone set that are available for use by transmitters. 574 tones are used from the base tone set, with the rest turned off to avoid the HAM bands.

In OFDM systems, the choice of symbol rate is a critical aspect. The PLC-AV symbol rate is set to 31.25 kHz and implemented with a practical 2048-point FFT. The smaller symbol rate reduces Inter-symbol interference (ISI) and entirely eliminates the use of a cyclic prefix (CP). CP overhead in HP 1.0 [1] by contrast is 40%. The nominal PHY data rate is 179 Mbps.

Time is slotted and grouped in a Frame that is 4096 symbols long. A Frame has 256 slots. The CCo transmits a Beacon with control information and timing reference for synchronization once at the beginning of each frame. The PHY defines the modulation and other parameters such as preamble length and coding and interleaving parameters, for a range of PHY "channels" which includes the Beacon.

The key features of the PLC-AV PHY are described below:

- Filtered OFDM: In traditional OFDM, the tones overlap in frequency and remain orthogonal in flat channels, but performance degrades significantly in frequency selective channels like powerlines due to Inter Channel Interference (ICI). Filtered OFDM results in non-overlapping tones with virtually no ICI. This approach has two very significant benefits:
  - ○ Flexible notching of HAM and other prohibited bands: Tones can simply be switched off to meet the out of band emissions requirements in different regulatory domains, without any additional filtering. Costly and complex programmable notch filters are not required.
  - ○ FDM Access is enabled: The sharp drop off in the spectrum of each tone allows multiple users to operate simultaneously in the 4-28 MHz with the CCo assigning different tone sets (even non-contiguous tones) to users for simultaneous transmission.
- Advanced and flexible modulation: The PHY supports both coherent and differential modulation types with a range of modulation densities on each tone. These include coherent QAM modulation from BPSK to 1024 QAM, Differential PSK from DBPSK to 64 DPSK and a novel modulation method invented here called Differential Amplitude and Phase Shift Keying (DAPSK). In DAPSK, a portion of the transmitted data is mapped to an amplitude level and the remainder to a change in tone phase. DAPSK modulation densities range from 8-256 DAPSK.
- Pilot assisted reception: Pilots have known but random patterns for robust unbiased reception. Pilot tone(s) allow symbol timing recovery. Diversity in pilot tones provides robust recovery in frequency selective channels. Pilot tones are used for timing recovery. Pilot symbols are used for gain and phase recovery and frequency estimation. While pilot tones and symbols add overhead, this is easily justified by the large capacity gains obtained from the use of higher modulation densities.
- Reed-Solomon (RS) coding and Interleaving: For unicast data communications, the data block size as well as the strength of the code is configurable. The size of the RS data block ranges from 55-255 bytes in size with 0-20 RS parity bits in a block. The interleaver depth ranges from 0-255 blocks. For broadcast channels, increased robustness is achieved by repetition of data.
- Channel Estimation: One of the most important factors affecting performance is the channel estimation function. This function produces the bit loading estimate (BLE) per tone. The BLE includes the best modulation density, modulation type and coding parameters possible while achieving a minimum BER. The source and destination devices via the exchange of a channel estimation sequence compute the BLEs for all 574 tones. Since the channel transfer function is coupled to the AC line cycle and interferers are often periodic, the channel estimation algorithm may

compute multiple "tone maps" containing the BLEs and the devices use different tone maps for different portions of the AC line cycle or the time Frame. The protocol supports the generation and distribution of the tone maps between devices and the devices and the CCo, with run-length encoding for compression.

4. MAC

The PLC-AV system supports both contention access and contention free access protocols. The contention access protocol is Slotted ALOHA with random back-off. Contention access is strictly used for control message exchange and not for data transmissions. In either case, devices use time division duplexing to alternate transmission and reception. All unicast and multicast data communications use the joint frequency-time division access method (OFDMA) enabled by the Filtered OFDM PHY described above. The system can easily default to TDM access only. A comprehensive comparison of the performance of the TDMA and OFDMA modes is described in [4]. In OFDMA mode, the BW is allocated to a pair of devices in terms of a set of frequency tones and time slots within a frame. Neither the assigned tones nor time slots are required to be contiguous. In the TDMA mode, the capacity assignment consists purely of time slots. The support of both modes provides the systems with the flexibility to selectively exploit the advantages of each access method.

TDM access has the advantage of requiring a much simpler AFE design due to smaller dynamic range. Further, in the TDM mode, near-far problems which degrade capacity can be avoided. The OFDMA mode also requires guard times and guard tones between frequency and time allocations made to different transmitters. This increases the protocol overhead of OFDMA compared to TDMA.

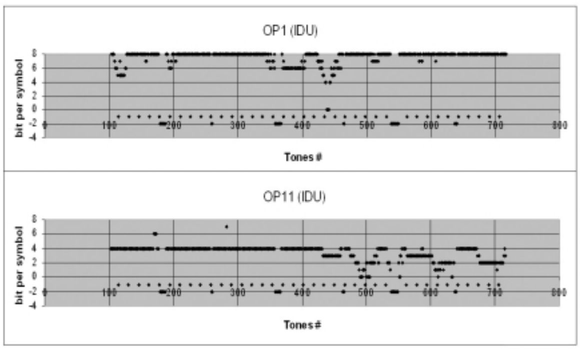

Fig. 4 BLEs for two OPs in an IDU.

OFDMA, however, can deliver significantly higher capacity when different outlet pairs (OPs) exhibit a wide variability in the performance (capacity) of individual tones. This situation is depicted in **Fig. 4**. The BLEs for two OPs measured in an actual independent dwelling unit indicate how frequency selective the performance can be between OPs, with one OP having much better performance in the lower frequencies. The OFDMA scheduler in this case would assign the lower frequencies to OP 11 and the higher frequencies to OP 1, thereby improving system capacity. TDMA does not provide this level of discrimination and hence OFDMA yields significant performance benefits in the powerline environment at the cost of complexity.

Important aspects of the MAC are described below:

- Scheduling: Scheduling of BW in the OFDMA modem is more complex because of the two dimensional admission control and BW assignment problem. SLA has developed a family of OFDMA schedulers which trade-off complexity and performance and optimize different figures of merit, such as, the total system capacity, number of admitted connections, the residual free capacity, the fragmentation in the frequency-time slot map, under constraints on the number of blocks of tones and slots assigned, transmit power etc.
- Sounding: OFDMA scheduling requires that the CCo have knowledge about the good and bad frequencies for each OP. Since the interference and transfer function change with time, the BLE estimates for each OP have to be regularly updated at the CCo. This information is collected via the process called Sounding. A broadcast message, with known modulation parameters, called the Discovery Beacon is transmitted, at scheduled time intervals by every device in the network. Every other device computes the BLE for the particular OP based on the reception of this broadcast. Periodically, the CCo polls individual devices and collects the BLE information for all links terminating on that device. The CCo creates and maintains a global repository of tone maps that are then used for tone selection by the OFDMA scheduler. The Sounding process is a low duty cycle background process.
- Connection Management: The PLC-AV MAC is connection oriented. All data communications is carried over logical "connections" identified uniquely by a global Connection ID and QoS specification. Broadcast transmissions are also supported. However, since true broadcasts require the lowest common

modulation parameters in order to reach all devices in the network, broadcast can be very expensive in bandwidth terms. Multicast connections using OFDMA can be supported in two ways: a single frequency -time allocation is used by the source and all destinations in the MCAST group, or, the MCAST could be carried over several unicast point-point links. In the latter case, the BLEs and link capacity can be optimized for each source-destination pair. The CCo can determine the optimal multicast method.

- QoS Specification : The QoS requirements of a connection are specified in the Connection Specification (CSPEC) . The CSPEC is analogous to the TSPEC concept in 802.11e [2] and comprises of two parts. The actual QoS parameters including max. delay, jitter, max-min data rates, TXOP sizes and gaps etc. are specified in one part. The CINFO comprises the second part and describes what MAC functions are applicable to the particular connection, including delay compensation, concatenation, fragmentation, encryption etc. The CSPEC is created by the MAC in the source device and monitored by the CCo and the devices. The CCo and devices also use the CSPEC to turn on/off specific functions and for BW allocation and reconfiguration.
- ARQ: The MAC supports a selective repeat ARQ scheme for point to point links. The max block size is fixed to 255 bytes in order to support fast retransmissions as required by AV applications such as HDTV. A novel repeated partial-ACK function is used to make broadcasts more reliable.

5. Network Management Functions

The MAC control plane in PLC-AV supports several novel functions that are critical to the management of the ad-hoc PLC network architecture described in Section II. Some of these functions are described below:

- Security and key management: All data and control messages, except the Beacon, are encrypted using AES 128-bit encryption. The network supports two encryption keys: a static Device key (DKEY) and a dynamic network encryption key (NKEY). Devices use the DKEY to encrypt the associate request message before joining a network. The CCo, if it admits a device, uses the DKEY to encrypt and send the NKEY. The CCo updates the NKEY periodically and informs all associated devices in the network of the new NKEY using their respective DKEYs. All communications from an associated device use the NKEY.
- Proxy Networking and Hidden Devices: The powerline environment gives rise to no-connects on a small percentage of links. When Devices cannot communicate with the CCo, they are termed hidden devices (HDEVs). The Discover Beacon transmitted during the topology discovery process contains the schedule for the subsequent time Frame. HDEVs scan the channel until they hear a Discover Beacon, and then decode the schedule to determine the location of a contention period within the frame. The HDEV transmits an encrypted associate request to the device that transmitted the Discover Beacon (called proxy device) in the contention period. The proxy device relays this message to the CCo. The CCo responds to the HDEV via the proxy device with the NKEY. The CCo instantiates a proxy network upon the detection of a HDEV and appoints a Proxy Coordinator (PCo). The PCo may be different from the proxy device. The PCo retransmits the main Beacon every frame at a scheduled time slot. All communications between the CCo and the HDEVs in a PN are relayed through the PCo.
- Topology Discovery: The topology discovery process consists of the broadcast of Discover Beacons in round robin fashion by all devices in the network at times scheduled by the CCo. The Discover Beacon echoes the schedule indicated in the main Beacon of the frame in which it is transmitted and carries the MAC address and device class/capability information of the transmitting device. All devices receiving the Discover Beacons contrast and update their Topology Tables, which contain the Discovered Node Lists (MAC addresses of devices from whom Discover Beacons have been received, their device classes and capabilities). The topology table may also contain a BLE for a particular source-destination pair constructed by the sounding

Table 1 Order of preference in selection of CCO.

Order	Criteria	Note
1	Device Class/ Device Capability	Highest class is preferred.
2	Number of Discovered devices in DISCOVERED_NODE_LIST	Higher is preferred
3	Activity Indicator (Fraction of time device is busy)	Lower is preferred
4	Capacity (Best average SNR on Discover Beacons)	Higher is preferred
5	Other (vendor defined)	

process that is based on the Discover Beacon also.

- Selection and handover of CCo functions: The choice of the CCo is critical to the performance of the PLC-AV system. The ideal CCo is selected through an analysis of information in the Topology Table and an existing CCo may transfer its functions to a more suitable device that is so identified. Since there are multiple criteria by which a CCo may be appointed, the order of precedence in **Table 1** is proposed. If there is a tie among devices in the selection process, the CCo may choose one of the candidate nodes at random to be the new CCo.
- Multiple Network Coordination: Multiple independent networks within a home or in neighboring homes can interfere in the absence of isolation filters. In order to preserve capacity and QoS within the network coordination between the neighboring networks is required. Two coordination methods have been developed- the first method based on explicit exchange of coordination and BW sharing messages between the CCos of the interfering networks, and the second method based on implicit interpretation of schedules in Beacon transmissions of each network with no explicit messaging. The second method is described in greater detail in [5]. A key concept in both methods is the definition of the Interfering Network List (group of networks whose CCos can hear one another) and the localization of all coordination to the INL cluster. This alleviates the problem of having a single CCo make all the BW sharing decisions for all networks. Instead, networks in an INL are bound to share on a fair basis. Another key concept is the reuse of the spectrum by different INLs. Unfortunately, the benefits of coordination diminish rapidly with increase in the size of the INL and size of individual networks as shown in [5]. At some point, as the scale and size of the INL networks grow, all networks see better performance by operating in a contention access CSMA mode. Hence, the coordination protocols also define methods to transition to and from a CSMA mode of operation.

6. Performance

A prototype implementation of the PLC-AV system described above was extensively tested in homes in the US and Europe. The homes consisted of both apartments and independent dwelling units (IDUs), with square footage ranging from <1000 sq ft to > 3000 sq ft. Testing consisted of scenarios with and without specific interfering appliances in the networks. The interference sources included halogen lamps, dimmers, X-10 devices, phone chargers, power supplies etc.

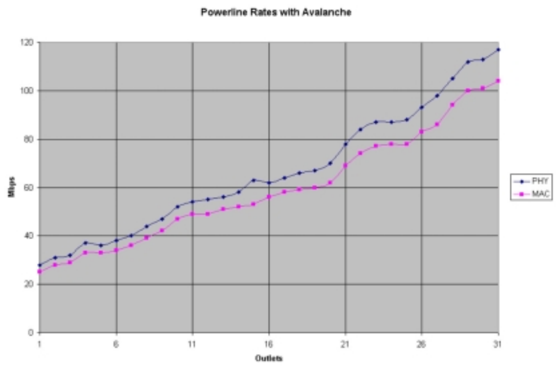

Fig. 5 MAC and PHY data rates for PLC-AV.

The MAC and PHY performance is shown in **Fig. 5**. The X-axis shows the number of OPs providing a particular data rate shown on the Y-axis. The MAC efficiency is > 70%. 100% of the OPs measured provided a MAC throughput higher than 20 Mbps. This meets the primary capacity and coverage target - the support of a single HDTV channel in > 98% of the OPs. The simultaneous transmission of additional HDTV and SDTV streams as well as IP applications is clearly feasible in a very large % of the OPs. These figures are average data rates and instantaneous data rates can show variability due to factors described earlier. The PHY and MAC mechanisms demonstrably ameliorate and even advantageously exploit these variations.

The performance of the OFDMA and TDM access modes was evaluated through simulations of the schedulers running on empirical data. The BLEs for 15 OPs were measured using a prototype implementation of the OFDM PHY, in an IDU and an apartment. TDMA and OFDMA schedulers were then used to determine the BW resource required to support a single HDTV channel. The BW resource was identified as the number of frequency-time slots or symbols needed to support a single HDTV stream, which is the primary application of interest for PLC-AV. The capacity and efficiency comparisons were made by computing the residual symbols and residual capacities for each OP. The residual symbols are the free symbols available after a single HDTV stream has been established. These residual symbols can be used by another OP, for applications such as IP or another HDTV stream. The residual capacity for each remaining OP (not carrying the

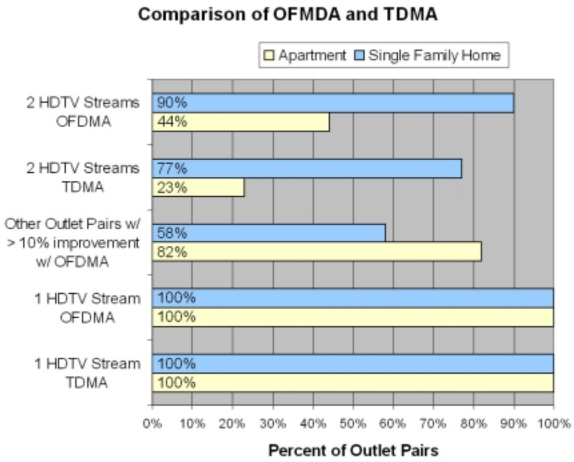

Fig. 6 Comparison of OFDMA and TDMA.

HDTV stream) is also computed for both OFDMA and TDMA and the number of such OPs showing a substantial capacity improvement (over 10%) is determined.

The results of this comparison are shown in **Fig. 6** and further details described in [4]. Each outlet pair can support 1 HDTV connection under both TDMA and OFDMA schedulers (100% Coverage). On average, 82% and 58% of the OPs in the Apartment and IDU, respectively, showed 10% or more improvement in their residual capacity, given that 1 HDTV connection was already setup in the same network. This indicates that OFDMA provides a significant advantage over TDMA in both efficiency of utilization of BW resources (how many OFDM symbols required to support the service) as well as system capacity (how may users or applications or BW in bps can be supported). A richer mix of applications such as web browsing, VOIP, etc. can thus be supported.

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