Multimedia Home Ethernets

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Abstract—**This paper evaluates various networking technologies to satisfy audio/video requirements in the home. It further advocates Ethernet as the backbone network technology in the home, identifying necessary enhancements so as to accommodate consumer electronics applications, in addition to computer devices.**

Index Terms—**Audio/Video streams, consumer electronics, isochronous and asynchronous transport.**

I. Introduction

Consumer electronics (CEs) have always enjoyed center-stage in residences. However, since personal computers (PCs) became a necessity, computers have become commonplace in people's homes as well. Moreover, printers, servers, as well as modems (dsl, cable) are also present in at least one third of US households. CE devices have used a myriad of technologies for interconnection in the home, including USB, 1394, Bluetooth. Meanwhile, PCs usually utilize Ethernet in its various versions (Cat5, Wireless - 802.11) for interconnection. The major challenge in supporting CE applications by a network technology comes from Audio/Video stringent Quality of Service requirements, illustrated in Table I.

Currently, networks in the home are largely used to connect computer equipment such as desktops, laptops, printers and scanners. However, despite the pervasive presence of CE devices in the home, such as TV sets and stereo systems, an insignificant number of such devices are interconnected via a network of any kind. In order to interconnect CE devices, a home network must be able to accommodate the applications listed in Table I as a minimum. Moreover, the technology must be "plug-and-play", i.e., with minimum installation complexity and zero maintenance support.

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TABLE I.
A/V APPLICATIONS – QOS REQUIREMENTS

Application	Requirements		
	Bandwidth	Latency	Jitter
HDTV	25 Mbps	300 msec	500 nsec
SDTV	4 Mbps	300 msec	500 nsec
DVD	6 Mbps	300 msec	500 nsec
VoIP	64 Mbps	10 msec	10000 nsec
Gaming	0.1 Mbps	10 msec	?
Video Conferencing	1 Mbps	75 msec	10000 nsec

II. Related Work

There is a myriad of topics currently being researched on multimedia home networks. Few of them focus on wired Ethernet as a backbone technology in the home.

A. Ethernet QoS Support

Regarding Ethernet QoS support, [1] proposes a change in the Ethernet 802.3 shared Medium Access Control (MAC) to support QoS needed by multimedia streams. In contrast, [2] proposes a token-passing protocol to support QoS in generic shared media, such as Ethernet, HomePNA, and Powerline. In our work, we assume full duplex Ethernet interfaces in the home backbone, so as to avoid lack of QoS support of a shared medium. Obviously, this implies that QoS must be supported by bridges in the home. We advocate the usage of a reservation protocol, and priority mechanism for this purpose. Shared medium Ethernet segments can still be used between bridges and end-points (no contention).

B. Multimedia Streaming in the Home

Recent papers focus on the support of multimedia streaming in the home by layer three and higher protocols. In [3], the authors describe an implementation of a multimedia content delivery system that includes a multimedia center, client players, and a PDA based network controller, to query multimedia databases and establish RTP based video streams across a network. Similarly, [4] builds an application association structure on top of RTP/RSTP/SIP to support streaming applications in the home. These approaches do not address the support of the underlying network on buffering, routing, and switching to multimedia stream requirements, such as delay, jitter, and data loss.

This paper advocates the use of Ethernet technology as a backbone network in the home. The paper introduces enhancements to current Ethernet technology so as to support audio/video streams. To our knowledge, this is the first contribution to both advocate a backbone Ethernet network in the home, as well as address Ethernet enhancements, such as resource reservation and time/synchronization protocols to support A/V streams. We first review prominent wired and wireless technologies, and their suitability to support A/V streams in the home. Then, we present enhancements to Ethernet technology to support A/V streams.

III. Communication Technologies in the Home

A. Networking Technologies

IEEE 1394. Initially designed to interconnect computers to peripherals, 1394 (also known as FireWire) technology has been used for interconnecting digital audio and video equipment [5]. The technology consists of a external bus that supports speeds of up to 400Mbps (1394a) and 800Mbps (1394b) - faster speeds may be on the way. The technology is able to connect up to 64 devices, and supports isochronous data - that is, data is delivered at a guaranteed rate and stringent timing constraints, which makes it ideal for audio and video applications. Electrical interface includes power, supplying from 8V-40V at up to 1.5A. One shortcoming is that the technology is constrained to "no-loop" connectivity, so in general interconnection topology gets constrained to daisy-chain or tree topologies. 1394 bridges are necessary to support arbitrary topologies.

Currently, MP3 players, Digital Video Cameras, Digital TVs (HDTV), Set-top boxes, Satellite receivers, audio/video receivers, Digital Video Recorders, DVD players/recorders, and CD players/recorders come equipped with FireWire interfaces. Therefore, IEEE 1394 is well positioned to play a significant role in the home environment.

USB. Universal Serial Bus is a serial bus initially developed for connecting peripherals at 12 Mbps speeds, although more recent USB2.0 allows up to 480Mbps [6]. USB ports are designed to be hot-pluggable. The bus technology provides daisy-chained connectivity, so network topology is limited. As with any bus technology, bus arbitration needs to be performed to avoid collisions. Host PC to peripherals is the common connectivity mode, where the host PC controls the USB bus. Latest USB developments allow peripheral devices to act either as a host or as a controlled device, so point-to-point connectivity between two peripherals take place by a negotiation between the parties as to who controls the bus (host negotiation protocol) [7]. Although isochronous transfer is somehow supported by USB 2.0 specifications [6] via periodic frame list data structures that are visited every 125 uSec, resource allocation strategies over the serial bus are not specified. Hence, USB specification does not provide either an absolute or probabilistic based transmission guarantees. Resource allocation over various buses has been researched recently [8]. Huang et al. [9] propose real-time scheduling and admission control algorithms to support isochronous traffic over USB 2.0/1.1.

Despite these current advances, USB technology lacks bridging capabilities to be a strong candidate for a home backbone network. Bridging can be realized as a natural extension from point-to-point connectivity and host negotiation feature. However, dual-role (host/peripheral) USB interfaces are not required to support all USB devices, so ubiquitous USB connectivity is not guaranteed, which could cause connectivity problems in the home. Therefore, for practical purposes, a PC host supporting all USB types of devices would need to be used, limiting home network topology. Moreover, it is not clear whether speeds of the order of Gbps will be supported in the near future.

Power Line. Communications over power lines have been studied for a number of years. The various types of noise, as well as unfriendly cables characteristics, which were developed without any concern for communication's applications, severely limit transmission speed. In the home environment, low voltage power lines suffer from noise caused by various types of network appliances, from light dimmers to television sets. Signals are modulated either into the current or voltage levels of the power line. To avoid noise at specific frequencies, spread-spectrum frequency hop modulation is preferred for power line communications in the home. Modulation schemes that appropriately cope with power line transmission impediments are currently being researched [10]. In addition, Forward Error Correction schemes can be used to improve bit error rates. Moreover, there is an initiative to create a Power Line communications technology to serve both data (internet access) as well as audio/video (consumer electronics) in the home [13]. A HomePlug 1.0 specification for data traffic was produced in 2000, whereas a HomePlug AV specification by 2005. A Central Coordinator of the PL channel arbitrates the channel transmission opportunities, so as to meet tight latency and jitter requirements of AV streams via a TDMA frame structure[14]. Field experiments of digital

TV transmission over a HomePlug 1.0 compliant home network has demonstrated the feasibility of sustaining low quality multiple video streams in the home (aggregated speeds of 15Mbps [15]). HomePlug 2.0 is expected to deliver up to 85Mbps, which is adequate for DVD quality video applications [14].

Due to limited bandwidth, power line networks are most useful to implement home appliance control systems [11], where simple home appliances such as air-conditioning, refrigerators, lighting and sensors have their electricity and gas usage controlled by a home management system. For multimedia applications, especial coding and transmission techniques might have to be used to withstand packet losses in the power line channel [12]. Unfortunately, especial encoders/decoders that operate over "unfriendly" channels are not a good solution to Consumer Electronics industry, where the margins of profit are very slim, hence simplicity and economy of scale are at a premium. In addition, the various types of cabling, the dependency of the line impedance with the number and kind of home appliances, together with diverse frequency transmission regulations around the world make it difficult to leverage the wide deployment of this medium in home networking. In addition, power line is essentially a shared medium, hence a shared medium access is needed. Meanwhile, it is interesting to notice that there is an opposite trend in bringing power into Ethernet technology [16], already very successful in low powered applications such as VoIP telephones, with promise to increase power in the near future [17].

Home PNA. Home Phoneline Networking Alliance is an industrial forum initiative to develop specifications for home networking using existing telephone wiring [18]. The first specification, HomePNA 1.0, supports data rates of 1Mbps. A second specification, HomePNA 2.0, supports speeds up to 16Mbps. It uses an Adaptive Quadrature Amplitude Modulation (AQAM), with adaptable modulation levels ranging from 4 to 256, depending on the channel quality. Of concern is the Inter-Symbol Interference (ISI) that arises from severe channel conditions of phone lines. Together with limited bandwidth, the technology may not be suitable for carrying multiple high definition video streams.

Ethernet. Ethernet technology can be seen today as a collection of standard documents, including various transmission (wired/wireless) interfaces, as well as networking protocols. Official IEEE Ethernet documents are issued by the 802 standardization body. The physical wired interfaces of Ethernet technology are standardized by the IEEE 802.3 standardization group, which has defined interfaces with a variety of characteristics, such as copper/fiber medium, half/full duplex operation modes, and 10/100Mbps, and even 1 Gbps speeds [19]. 802.11 group is responsible for standardization of wireless interfaces, most commonly known as WiFi technology [20]. Ethernet was designed to be a plug-and-play, unmanaged network technology. Among its features, it allows arbitrary network topology, supports interface speed auto-negotiation (10/100Mbps), and supports Virtual LANs. Ethernet is pervasive in Local Area Networks (LANs) across the globe, connecting computers, printers, and other devices in the office. Moreover, Wireless Ethernet [20] operates on an unlicensed radio frequency, providing wireless shared connectivity of short reach, around 100 meters. Today, a significant number of homes in the US also use Ethernet to connect home PCs, printers, and data network gear such as home access points and wireless routers. However, Ethernet was not designed to connect Consumer Electronic devices, or any real time application with stringent delay/jitter end-to-end requirements.

Wireless 1394. Wireless 1394 is a wireless bus, as opposed to a 1394 cable bus [21], composed of a hub (base) station, and leaf stations. The hub station is the central controller of the bus, although data communication can take place between any two leaf devices without the hub participation. The hub station is responsible for maintaining the frame structure, sending cycle-time information, partitioning the air interface between asynchronous and isochronous traffic, monitoring the status of all wireless stations, as well as controlling access between stations. The role of the hub can be passed to other wireless devices. Within the 5.2Ghz frequency band, 20Mhz channels of 40Mbps capacity, using Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme, are established. A wireless 1394 radio measures the received power, as well as detects synchronization with other stations via packet preamble. The highly adaptive modulation modes, resulting on a widely variable channel bit rate, from 6-70Mbps, depending on propagation and interference conditions in the home, makes it difficult to use the technology to support multiple CE high definition video streams in the home without eventual service degradation.

Bluetooth. Bluetooth is a network standard for short range, low power radio based wireless communication. Its wide adoption throughout a variety of devices such as communication/PC devices (PDAs, cell-phones, laptops), peripherals (mice, keyboards, joysticks, printers), consumer electronics (cameras, headsets, speakers, stereo receivers), and embedded applications (automobile power locks, MIDI musical instruments) was a result of the Bluetooth Special Interest Group formed by Ericsson, Intel, IBM, Nokia and Toshiba in 1998, which issued an open and freely available Bluetooth standard [22]. It has become a standard for Wireless Personal Area Network [23]. A Bluetooth transceiver uses a frequency-hopping spread spectrum scheme over an unlicensed 2.4Ghz Industrial, Scientific, Medical (ISM) frequency band. The number of channels available ranges from 20-80 channels, each with 1Mbps. FCC regulations restrict the maximum peak power output to 1 watt, with each device required to operate on a channel for no longer than 0.4 seconds within any 30 second period. These restrictions are in place so as to minimize the interference in the ISM band, which is also used by 802.11 b/g devices, Home RF devices, portable phones and microwave ovens. A transceiver hops among the channels (FHSS) at a rate of 1600 hops per second, with a reach of 10 meters, although longer ranges can be achieved via amplifiers. Time division duplexing (TDD) and time division multiple access (TDMA) are used for providing isochronous and asynchronous transmission, respectively. A single time slot consists of 625uSec, which is the length of a single slot packet, used for isochronous services. Link control data in the packet is protected by a Forward Error Correcting (FEC) code. Bluetooth devices organize themselves into piconets of at most 8 active devices each, one of them being a master, and the others slaves. More slaves (up to 255) are possible, if all but 7 slaves are inactive (parked). Communication takes place between master and slaves only, so there is no slave to slave direct communication. The master station exchanges clock information with slaves prior to any slave to join the piconet. Slaves are polled for data transmission, and may transmit only in the time slot immediately following the pooling. A different frequency is used at each time slot. Piconets can be connected by Bluetooth bridges, which extend the reachability of Bluetooth networks somewhat by providing multi-hop communication between Bluetooth devices.

Bluetooth short range and low power characteristics enable its interfaces to have a very small footprint and affordable cost, making it perhaps the preferred technology for connecting peripheral devices. However, its limited bandwidth, very short range and unlicensed band (ISM) operation, hence prone to interference [24], makes Bluetooth technology unsuitable for high bandwidth CE applications such as high definition video streaming. Moreover, its voice support does not warrant Bluetooth to transmit high quality audio, a must in most consumer electronics applications.

Home RF. Home RF was an industry initiative to create a wireless standard that deals with interoperability issues among various wireless technologies and products in the home [25]. HomeRF specification defines a new common HomeRF MAC and physical layers, supporting both voice and data networking in the home. Moreover, a Shared Wireless Access Protocol (SWAP) [26] for radio-based home networks aims at defining an air interface that supports both wireless voice and LAN data services in the home, and also ensure interoperability among wireless products across the PC and consumer electronics industry. SWAP operates in the 2.4Ghz ISM band, and resembles the IEEE 802.11 standards in the physical layer. For modulation, it uses a Frequency-Hopping Spread Spectrum, with channel hopping frequency of 50/sec. The protocol supports both a Time Division Multiple Access (TDMA) service for interactive voice and time-critical applications, as well as a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) service for data applications. A home network based on SWAP system operates either on an ad-hoc manner (peer-to-peer), for data applications, or controlled by an Access Point (master-slave), on a connection oriented manner. The technology has lost momentum with the widespread adoption of WiFi technology.

802.11. As mentioned earlier, wireless Ethernet operates on unlicensed radio frequencies of 2.4 [27] and 5 Ghz [28], providing wireless shared connectivity of short reach, around 100 meters. Two types of PHY layers exist: direct-sequence spread spectrum (DSSS) and frequency-hopping spread spectrum (FHSS). Currently, there are several types of radio: 802.11a [28] uses unlicensed 5Ghz band and OFDM to deliver up to 54Mbps; 802.11b [27] uses a complementary code keying (CCK) modulation to deliver up to 11Mbps; 802.11g uses either single carrier trellis-coded 8-phase shift keying (PSK) modulation or OFDM to deliver rates in excess of 22Mbps. As both 2.4 and 5Ghz frequency bands are unlicensed, interference among multiple base stations and other devices, such as microwaves, is commonplace. Therefore, high bandwidth, QoS demanding applications such as high definition video streams may require new radio interfaces over licensed bands and with QoS support. Regardless of future Ethernet wireless advances, a wired Ethernet solution is unquestionably preferred as a backbone network technology for its large bandwidth and immunity to noise.

1394+UWB. Ultra Wide Band technologies use extremely low power pulses of radio energy spread across a wide range of frequencies, hence it is used for short distances only. The technology characteristics include: high capacity, by spreading bandwidth over a wide range of frequencies; low probability of multipath fading, due to the usage of pulses rather than sinusoidal waves; immunity to interference; frequency diversity. Home network solutions using a wired/wireless IEEE 1394 for backbone integrated with UWB Bus for short reach have been recently proposed [29, 30].

Tables II and III summarize the characteristics of both wired and wireless technologies in the home. Although many of these networking technologies are likely to play some role in connecting CE devices in the home, the technologies most likely to be used in a backbone home networking of the future are Ethernet and IEEE 1394. IEEE 1394 is well adopted by CE devices, whereas Ethernet interfaces are ubiquitous among computer electronic devices. Perhaps a merging between these two technologies may lie ahead in a not so distant future.

In addition, although mobility is important for a specific set of devices (light weight, low powered),

TABLE II.
WIRELESS TECHNOLOGIES IN THE HOME

	Technology				
	Bluetooth	HomeRF	802.11a	Wireless 1394	1394+UWB
Spectrum	2.4Ghz (ISM)	2.4Ghz (ISM)	5.2Ghz	5.2Ghz	3.1-10.6Ghz
Peak Rate	~720kb/s	0.8-1.6Mb/s	~54Mb/s	~70Mb/s	>100Mb/s (~400Mb/s)
Modulation	FHSS 1600h/s	FHSS 50h/s	OFDM	OFDM	TH-PPM PAM Biphase PM
Range	< 10m	< 50m	~ 50m	10-20m	< 10m
Topology	P2P, MS	P2P MS2BS	MS2BS	P2P multihop	P2P multihop
Real Time	Yes	Yes	No	Yes	Yes
Appl.	Mobile ph PDAs	PC Peripherals Mobile T	IP data	A/V IP data	A/V IP data

TABLE III.
WIRELINE TECHNOLOGIES IN THE HOME

	Technology				
	PowerLine	HomePNA	USB	802.3	1394
Data Rates	10Kb/s (~10Mb/s)	1 Mb/s (~10 Mb/s)	1.5/12 Mb/s (~480Mb/s)	100Mb/s (~1Gb/s)	~400Mb/s ~800Mb/s (~3.2Gb/s)
Real Time	No	No	Yes	No	Yes
Topology	P2P	P2P	P2P w/bridge	P2P P2MP Mesh	P2P BUS
Appl.	Electronic Device control	Phones	PC peripherals	IP data	A/V, IP data

certain devices will not require mobility, e.g., flat panel screens, music centers, home video servers. Connecting these devices wirelessly is less than optimal, since wireless medium provides less bandwidth and is more prone to noise. Moreover, adaptive wireless interfaces result in potentially widely variable channel capacity (few Mbps to tens of Mbps), which makes it difficult to support bandwidth demanding QoS stringent applications, such as multiple high definition video streams.

B. Higher Layers - UPnP

UPnP technology defines an architecture for discovery and description of devices and its services, from simple binary-controlled device types to complex ones. The framework utilizes the Internet Protocol, HTTP, XML, and SOAP over TCP/UDP. In particular, the UPnP Forum has defined an A/V architecture for the audio/video entertainment in the home. Obviously, service description and discovery must ultimately be integrated into the home networking environment. Therefore, some networking devices in the home must interact with UPnP capable A/V devices. Hence, interworking issues between networking devices and UPnP ones have started to be addressed [31]. These include translation/encapsulation of SOAP messages into the network technology of choice, the representation of A/V devices connected to the home network as "complex" UPnP devices, e.g. a camcorder being a media server and media renderer [31].

Because UPnP protocols rely heavily on TCP/IP, a networking technology in the home that "blends" together with Internet Protocol facilitates UPnP/network integration. So, one may ask why not use routers in the home. The short answer is that it is an overkill – IETF protocols, such as routing, security, etc. are designed for networks fundamentally different than a home network environment. IETF protocols are aimed at networks of large scale, with various underlying data layer networks glued together, hence requiring quite heavy configuration and management tools and IT personnel. A home network is a small size, "plug-and-play" network with no IT personnel on site. Another issue is that service description based on XML/SOAP technology relies on URL/URI addresses, which then require DNS services to be translated into IP addresses. A home DNS service then may be required.

IV. ETHERNET AS AN INTEGRATED HOME SOLUTION

The strongest reason for using Ethernet as a converged solution in the home is the number of Ethernet ports shipped today. Few would argue that Ethernet has reached an unprecedented level of adoption worldwide, hence the extension of Ethernet technology to accommodate consumer electronics applications would enable economies of scale unmatched by any other network technology, a critical factor for consumer electronics market of slim profit margins. Another inherent advantage of Ethernet as a home backbone technology is that the Ethernet of today has evolved away from a shared medium to a full duplex switching technology, with truly networking features such as Virtual Local Area Networking (VLANs) and priority support [32].

The various networking technologies discussed previously are expected to be present in a future home network in some integrated way. Fig. 2 illustrates a converged CE/PC home network. A home gateway mediates access to the home by various media and service providers. Inside the home, an Ethernet backbone provides ubiquitous connectivity between both CE and PC devices. Legacy networking technologies, such as 1394, USB, Bluetooth, WiFi (802.11) will still be present, but as home network access technologies, bringing specific application streams into the home backbone network.

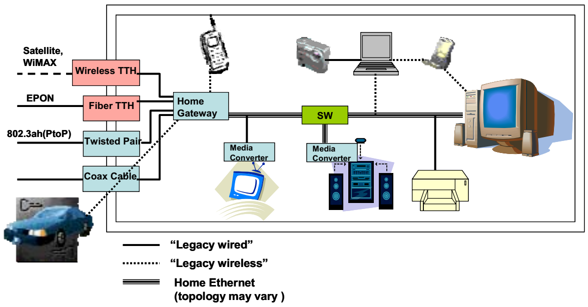

Figure 1. Converged CE and PC home network.

In order to accomplish the view illustrated in Fig. 1, audio/video applications in the home will require enhancements in current Ethernet technology. The following enhancements areas are foreseen.

A. *Delay and Jitter Performance*

Audio and video streams may be present in the home in various digital formats. Regardless of the format, delays in the network may impact greatly consumer experience of the A/V application. For instance, consumers may experience great discomfort during channel "flipping", if delay between pressing a button on a remote control and the actual change of channel is on the order of seconds. Applications with high level of interactivity, such as games, are likely to place requirements on network delays.

Regarding jitter, stringent network requirements are likely to be imposed. For digital audio, the CE industry has defined standard transmitter/receiver interfaces for A/D conversion, clock recovery, and D/A conversion. The capabilities of clock recovery are predicated on jitter and wander specifications, available for consumer and professional applications, which must be met by the transmission medium. Digital video may be available in a compressed or uncompressed form. Several standard sampling techniques result in various bit rates, ranging from roughly 150Mb/s (NTSC and PAL serial digital interfaces) to 1.5Gb/s (HDTV) signals. In addition, several digital formats may be used, such as MPEG2 and MPEG4. Regardless of the encoding techniques, video receivers are designed to work under specific transmission medium jitter requirements, for instance in clock recovery (usually via Phased Locked Loop-PLL techniques) and buffering procedures.

Therefore, new features from Ethernet technology to meet delay and jitter requirements for A/V applications in the home will be required. Synchronization mechanisms between application end-points, as well as the implementation of synchronous delivery of packets, similar to 1394, may be needed, especially to meet audio application requirements.

IEEE 1588[38] is a new standard for clock synchronization between devices interconnected by a communication system. Since synchronization mechanism within Ethernets will likely follow this standard, we present its main characteristics. 1588 describes distributed protocols, collectively called Precise Time Protocol (PTP), to provide synchronization between various clocks in a communication network. A single instance of the PTP runs on a given clock domain. Two main clock types are recognized: Ordinary/boundary, and transparent clocks. An ordinary clock possesses a single connection to the network, whereas a boundary clock has multiple connections, onto various synchronization domains. Ordinary/boundary clocks engage on a master/slaves relationship, where synchronization is executed by the slaves based on master clock information. Transparent clocks are elements in between the master and slaves, and relay messages from master to slave direction, in the process syntonizing (same frequency, but not same time count) itself with the master.

There are two protocols: a Best Master Clock (BMC) selection (leader election algorithm), and a synchronization protocol. Announce messages are relayed between the elements, for master selection, which is based on MAC ID, hop count, and preference parameter (to bias the selection of the master towards a better quality oscillator, for instance). Each ordinary/boundary clock collects announce messages from other ordinary/boundary clocks during a time interval, and based on the messages received each clock decides on a master clock [39].

The synchronization protocol basic message exchange is shown in Fig. 2. A sync message is launched by the master towards a slave at time t1 (measured by the master). If the master has hardware capabilities, it includes t1 timestamp information in the Sync message itself. Otherwise, the master sends an (optional) followUp message, with t1 timestamp information. In either case, the slave ends up with t2, the time of arrival of the original Sync message, and also t1, the time of its launch. In addition, the slave initiates a delayReq/delayResp handshake with the master, in order to estimate the propagation delay between master and slave. This handshake takes place less frequently than the sync message exchange, since propagation delays are expected to remain constant. Time epochs t3 and t4 define the time of launch/arrival of the delay request message. Once the slave is informed of t4 by the delayResp, it can calculate the mean propagation time between itself and its master by:

$$MPT = [(t2 - t1) + (t4 - t3)] / 2 \qquad (1)$$

and its offset from the master will be:

$$SlOffSet = t2 - t1 - MPT \qquad (2)$$

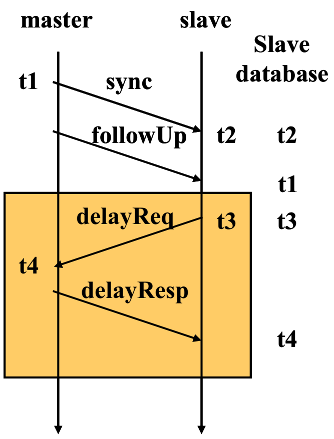

Fig. 2 Master/slave synchronization protocol

Transparent clocks forward master/slave message across, and in the process, it computes its own offset time from the master clock. Figure 3 illustrates the transparent clock role in the synchronization process.

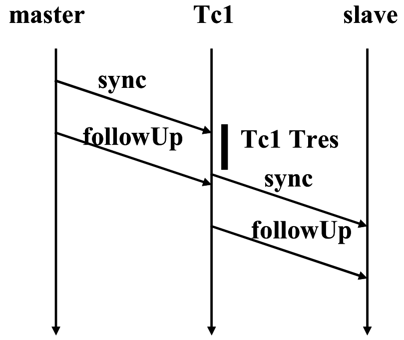

Fig. 3 Transparent clock participation in synchronization protocol

As it can be seen in the figure, a transparent clock (TC) relays Sync messages from a master (or other TC) to a slave (or other TC). The relay time of a sync message is referred to as the TC residence time, and its value is added to a time correction field in the sync (or follow up) messages, to be included in the computation of the slave offset time. Another time correction field contains the propagation delays of the TC incoming links, also used in the slave offset computation. These propagation delays are estimated by a message exchange similar in nature to the delayReq/delayResp handshake. The slave offset is then:

$$SlOffSet = t1 - t2 - Tpr + Tres \qquad (3)$$

where t1 is the launch epoch of the master Sync message and t2 its arrival time at the slave.

Various networking technologies already implement time/synchronization protocols. This brings the issue of time/sync domains and interoperability within the home. The ones most likely to interoperate with Ethernet time and synchronization mechanism are EPONs (Ethernet Passive Optical Networks, in the access network), 802.11 (there is a new time/sync protocol, 802.11v, for station localization purposes), and Bluetooth. Interworking functions between heterogeneous time domains will need to be devised.

There are several issues in supporting a timing and synchronization protocol within Ethernets. Firstly, bridges currently have no support for time-stamping frames. Timestamps must be measured for a given frame position (e.g., start of frame field), and the timing information must be attached to special frames such as Sync frames. Moreover, time domains must be protected from “leaks”. For instance, an access point belonging to a neighbor should never provide timing information to a neighbor home network. Another issue is the implementation of the clock distribution protocol such as 1588 across various media, such as wired and wireless Ethernets. The protocols will likely need adjustments and interworking functions. For instance, a wireless access point may fail to send a Sync or followUp frame, so the protocol should be robust to operate over heterogeneous media.

B. Traffic Prioritization

Data traffic is inherently lenient to delays and even loss, when retransmission mechanisms are available at end-points. For real-time streams, end-to-end delays are very strict, as illustrated in Table I. Therefore, it is necessary that delay sensitive traffic take precedence over data traffic when network resources are scarce. Today, a real-time stream, say MPEG stream, over an Ethernet network competes on the same basis with a file transfer stream. In the absence of an admission control mechanism, the file transfer may take the entire bandwidth of a path, preventing a real time stream to get across the network without excessive delay, causing image glitches unacceptable to such applications. Current Ethernet standards [32] allow for eight levels of traffic priority to be defined to traffic classes. However, the definition of which application is to be assigned to which class is not standardized. Moreover, nowadays, no Ethernet application interface generates traffic with high priority – priority bits are configured at bridges only, via management operations. But in the future, the assignment of applications to traffic classes may be standardized, or at least recommended so as to establish predictable end-to-end network services for given applications. CE audio and video streams then should get a high traffic class assignment, whereas file transfers would have lower priority.

C. Bandwidth Reservation

CE applications require a predictable transmission service by the underlying network. Since every network has a limited amount of resources, there must be some bandwidth allocation mechanism to ensure that audio and video streams are served appropriately, and not delayed at intermediate bridges due to congestion. Bridges currently do not support bandwidth allocation at any granularity, hence a mechanism for the accounting of the streams served at bridge ports versus a pre-defined amount needed for adequate stream transmission is needed. It is likely that the Generic Attribute Registration Protocol (GARP) be enhanced to provide the signaling necessary to allocate bridge resources along a home Ethernet. GARP is a protocol that allows end-stations to register attributes on bridge ports, as well as propagate such registrations across a LAN. One current application of GARP is Group Membership Registration Protocol (GMRP), which allows the registration of group membership along a LAN. This allows bridges' forward databases to mark which outgoing ports lead to members of a given group, so that multicast frame forwarding be done accordingly, preventing the flooding of frames across the entire network. In contrast, bandwidth reservation for A/V streams will require two phases, a registration and a reservation phase. State machines of the GMRP protocol can be leveraged for the A/V stream registration. However, new state machines will likely be used for the registration phase. The major differences between these two functions are:

Registration

- Symmetric protocol. All group registrars are similar
- Establishes identical registration state across all participants of a group
- Establishes identical registration state across all bridge ports of an active topology (a multicast tree)
- There is no registration failure

Reservation

- Asymmetric protocol. There is one talker and various listeners on an A/V stream application.
- Reservation state is established across a path talk/listener only, not along an entire multicast tree.
- Reservation request must be explicitly acknowledged (ack or nak). Reservation failure must be signaling back to the A/V application.

Once the signaling protocol to request network resources is in place, bridges must make sure that the granted requests are honored, so that A/V streams can be served with adequate quality.

Security is an issue that needs to be addressed in the home network. Registration and reservation functions must be protected by secure protocols.

D. Admission Control

Once network resources are allocated for application streams, the network must make sure that applications do not pump more traffic than expected. Moreover, once network capacity has been reached, new applications will be blocked from networking services. Each edge bridge in the home (bridge connected to one or more applications) must exercise admission control so as to avoid network capacity exhaustion. Moreover, higher layer protocols, such as TCP window flow control for data applications, are known to limit throughput performance in the presence of network congestion. Hence, admission control will benefit not only isochronous services, but also computer applications as well by limiting packet losses.

E. Stream Addressing

Consumer electronic A/V devices, such as home theaters and DVD players, typically come with various A/V plugs, each of which requiring proper connection with peer application devices, such as TV sets and speakers. As the variety of CE devices in the home gets large, the number of connections and wiring to be performed places a challenge for the average consumer. A converged home network must provide plug-and-play capabilities to applications of the future. This involves the aggregation of several audio/video streams into a single Ethernet network interface (as well as service discovery capabilities, already mentioned). As each of these A/V streams may go to different devices in the home, there must be a way for the home network to differentiate streams coming into/ going out of a single Ethernet interface, both at end-points, as well as in the middle of the network (for routing purposes). Multicast group MAC addresses are addresses that can be managed by a registration mechanism, and can be conveniently used for multipoint connectivity within Ethernets [33]. However, a single multicast MAC address per stream may incur on a large number of multicast addresses used. Currently, multicast addresses are rather the exception than the rule in bridged local area networks, so bridge design changes to accommodate a large number of multicast addresses may be needed. A possibility to reduce the number of multicast MAC addresses is to use VLAN tags for defining multipoint connectivity within the home. For instance, a home theater with surrounded sound could originate various audio signals, one for the right front speaker, one for left front speaker, one for rear left and another for rear right speakers, in addition to an uncompressed video signal. Although all these signals would come out of a single Ethernet interface with a given unicast MAC address, and destined to a single multicast MAC address, each frame stream could use a particular VLAN tag, assigned by the first bridge of the home network. Home theater receivers, such as speakers and flat panel TV sets could join a particular VLAN tag based stream, via registration protocols such as Group VLAN Registration Protocol [32]. This solution, however, requires strict regulations about the usage of the VLAN tag space to avoid tag collision. However, Digital Rights Management (DRM) issues may call for use of unicast MAC addresses to some CE applications.

F. Congestion Control

Consumer electronics traffic will likely have higher priority than data traffic generated by PCs in the home. Given the burstiness of some CE streams, it is likely that data traffic be dropped at the home network if no congestion control mechanism exists. TCP window flow control can be exercised at IP layer, for data streams. However, traffic oscillations resulting from TCP window flow control may impact adversely multimedia traffic, even if at low priority (Ethernet bridge frame schedulers are non-preemptive). Hence, a congestion control scheme at the Ethernet layer may prove valuable for loss sensitive traffic [34].

The idea is to equip Ethernet bridges with a feedback information mechanism to signal congestion back to end-stations, so that they slow their traffic rates exercised at the application end-points. Although an interoperable congestion control protocol is yet to be devised for Ethernets, its characteristics should be as follows: simple to implement; avoid/prevent frame loss; avoid traffic oscillations [40].

In [40], we have developed a control theoretical approach to the congestion problem in packet networks. We now use the approach to regulate non-real time traffic in a home environment. Each non-real time, but loss sensitive stream is model as in Fig. 4.

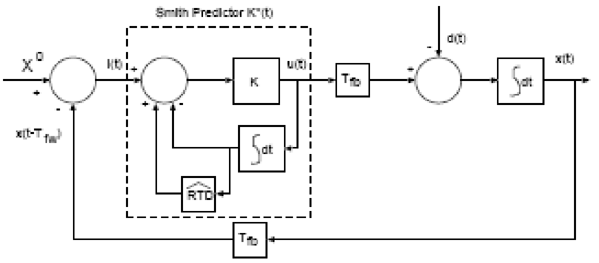

Fig. 4 Congestion control of non-real time traffic

with rate control equation given by:

$$u(t) = K\left[X^{o} - x(t - T_{fb}) - \int_{t-\widehat{RTD}}^{t} u(t')dt'\right] \quad (4)$$

where u(t) is the non-real time traffic input rate, X0 is the available buffer on each Ethernet switch, K is a gain parameter that defines the responsiveness of the controller, and RTD is the round trip delay of the stream. A discrete version of Eq. (4) is given by:

$$u(t_k) = K\,(X^{o} - x(t - T_{fb}) - \textstyle\sum_{\mathrm{RTD}} u(t_i)\Delta) \quad (5)$$

where Δ is the sample period of the system, which defines a timeout for rate computation at the sources. Fig. 5 depicts a five Ethernet switch home network, at which A/V traffic shares bandwidth resources with rate regulated non-real time traffic.

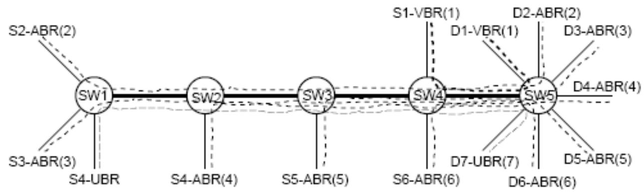

Fig. 5 Home network simulation scenario

The simulation scenario comprises one A/V real-time source, modeled as an on-off source – S1-VBR, five non real-time regulated sources, S2-S6 ABR, representing loss sensitive applications such as file transfers, and one best effort, non-regulated source, S7-UBR. Five switches comprise the home network[1]. Fig. 6 shows input rate dynamics for all sources. Fig. 7 reports on applications' throughput.

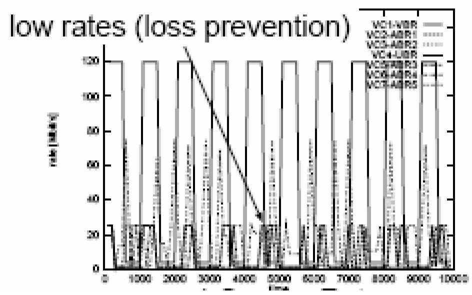

Fig. 6 Real-time and loss-sensitive non-real time traffic in the home

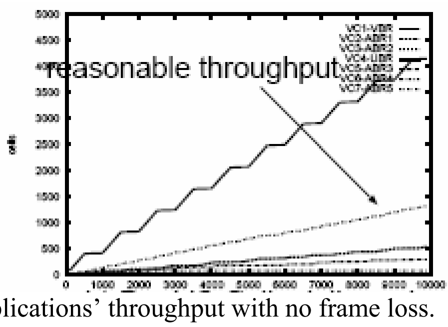

Fig. 7 Applications' throughput with no frame loss.

[1] IEEE 802.1 AVB Study Group currently envision a home network with at most seven bridges.

The on-off sources model real-time traffic, which takes up to 120Mb/s, or 12% of the Ethernet backbone speed of 1Gb/s. The traffic pattern shown in Fig. 6 may model an aggregate of compressed video traffic, or uncompressed video in the home. As shown in Fig. 6, loss sensitive non-real time traffic input rate is regulated around 20Mb/s, to prevent frame loss without interfering with real time traffic. Fig. 7 presents throughput measurements for all sources. Real-time traffic throughput does not get affected by the non real-time traffic because we attribute the highest priority to real-time traffic, whereas flow controlled traffic gets medium priority, and best effort lowest priority. Nonetheless, non real-time traffic still gets a reasonable throughput. No frame loss of medium priority traffic is detected.

V. Home Networks and Standards

There are several standardization and industry groups whose activities are related to home networks, and the convergence of consumer and computer electronics industries. The Digital Living Networking Alliance [35] is an industry group chartered to produce guidelines on how to achieve interoperability between home (PC and CE) devices, so as to provide an "out-of-the-box" experience to consumers. DLNA does not produce new standards, but rather references existing standards so as to ensure interoperability and easy of usage of devices connected to a home network. The UPnP Forum [36] is an industry group chartered to enable simple and robust connectivity among consumer electronics and computer electronics from various vendors. The general idea is to define a vendor agnostic device description, together with service discovery procedures, so as to ensure simple connectivity and interoperability of multi-vendor devices. To achieve these goals, the forum utilizes XML technology for the description of a variety of devices, such as media servers, gateways, wireless access points, cameras and printers, as well as the services they provide. Audio/Video Bridging Task Group [37] is an IEEE 802.1 task group chartered with enhancing Ethernet technology with features needed to accommodate Consumer Electronics devices and applications. Currently, the group is studying several enhancement mechanisms, such as bridge and end-point synchronization, A/V frame scheduling, bandwidth reservation, and admission control, so as to meet the stringent delay and jitter requirements of A/V streams. Although congestion management is being study by IEEE 802.1 for data center applications, a resulting congestion control protocol may be used by data servers in the home to avoid traffic oscillations and frame loss.

VI. Conclusion

In this paper, we have evaluated several wired and wireless network technologies as candidates for a converged consumer electronics and computer network in the home. We have advocated the usage of Ethernet as a converged CE and PC backbone technology to support audio and video applications, as well as described necessary enhancements to it. We are currently investigating issues related with the integration of home Ethernet and upper layers, such as UPnP, not addressed in this paper.

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