A New Paradigm for a Multi-services Cable Communications System

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Abstract

This paper proposes a flexible architecture for a multi-services cable communications system that not only supports telephony, data, and digital video services, but also potential future services. A unique network interface unit (NIU) at the home entry point functions as a hub to the in-home cable network, isolating the outside cable plant from any possible ingress from the home. It passes high-speed video data uninterrupted in the downstream direction, while remodulating low-speed data to an area in the 5-40 MHz band. The NIU always remodulates data flowing in the upstream direction between end-terminal devices and the headend. Adoption of an in-home network protocol based on the Universal Serial Bus (USB) modified for coax cable is an inexpensive way to form a link between the NIU and a plethora of USB devices that are appearing on the market. The USB protocol on the in-home network uses an efficient modulation scheme.

INTRODUCTION

The last few years the cable industry has actively pursued the introduction of new digital services over the hybrid fiber-coax (HFC) plant to supplement their more traditional revenue stream of the familiar analog broadcast and pay-per-view (PPV) services. Stand-alone offerings to subscribers include cable telephony, data, and digital video services. All of these services require different amounts of data with various transfer data rates and protocols. Some can tolerate delays, while others would suffer a loss in quality. They share the spectrum above the analog broadcast channels for the downstream direction (to the home), and below it for the upstream direction (to the headend).

Quadrature Amplitude Modulation (QAM) is one of the modulation schemes used in discrete bands in the downstream direction. Each 6 MHz analog channel supports approximately a 27 Mbps data stream for QAM-64, in which one symbol represents 6 bits, or a 35 Mbps data stream for QAM-256, in which one symbol represents 8 bits. The downstream data may represent a broadcast signal intended for all homes as in the case of digital video, or an encrypted message intended for one particular receiver.

The headend controls the upstream data flow using a time division multiple access (TDMA) approach to allow multiple subscribers to share the same frequency spectrum. The upstream signal path uses a Quadrature Phase Shift Keying (QPSK) or 16-QAM modulation scheme. The upstream data rate for each 2 MHz analog channel amounts to approximately 2.56 Mbps for QPSK. The cable plant reserves the 5-40 MHz band for the upstream return channels. Unfortunately, the cable return path presents some engineering challenges [1]. MSOs often use the lower 10 MHz of this band for network maintenance or find it unusable due to ingress. It effectively leaves only a 25 MHz band per node, still exposed to burst noise and ingress, for all services

The increasing demand for interactive services over a two-way cable plant creates problems in network management, channel allocation, maintenance, and operational support. As newer services, such as energy management, digital audio, home security and automation, electronic games, and others not yet imagined, supplement digital video, cable telephony, and data services, it becomes paramount to utilize the available upstream spectrum effectively. Sharing of frequency bands becomes mandatory in order to achieve acceptable upstream data rates.

Different economic models apply to the services offered over the HFC network. The MSO understands the models for digital video, telephony, and data very well. Often they are looked at as three individual services sharing one common transport medium. Although there are many components shared among the end-terminal devices, i.e., the components that convert the digital data streams into a usable format for each service, few companies are considering integrated solutions. Some companies are contemplating the combination of two services, such as a set-top box with a data port, or a digital phone with a data port. Others focus on a powerful box at the side of the house that combines video, data, and telephony services.

The lack of an integrated approach greatly hampers the deployment of additional services. Especially low bit rate services, such as energy management, home security, or home automation are prohibitively expensive to introduce as a cable service if they require a costly QAM receiver and QPSK transmitter. Cable companies will not get access to these services, and their corresponding revenue streams, as long as a simple and cost effective way to interface them to the cable plant is missing.

Headend equipment becomes more and more complex with the addition of each new service. Does the new service obtain its own upstream channel? What are the consequences in case of high bit error rates? How is spectrum management arranged? Which service controls the upstream channel allocation? What about power calibration and ranging between the headend and the many devices in the home? As the MSO adds services to the two-way cable plant, it becomes more difficult to manage a reliable communications link.

The first section of this paper focuses on the requirements and existing architectures for expanded cable services. The following section proposes an integrated architecture implementation that offers advantages over existing individually deployed cable services. The final section addresses some implementation issues for the proposed architecture.

MULTI-SERVICE REQUIREMENTS.

Expanded cable service requirements.

The characteristics of the various digital data services differ in significant ways. The wide range of applications requires different data rates, data packets, data flows, and error handling. Table 1 summarizes the important features of present and some future services. The table lists the service type with the associated data rate and data format. Other categories listed include the packet transfer delay, i.e., the time difference between the packet generation and the delivery; the effect of the variation in this delay; the effect of loss of packets; and means of error handling.

We may safely assume that the amount of data flowing toward the home far exceeds the amount of data originating from the home. This is especially true if digital video services are provided. As Table 1 reveals, the listed services can be divided into two broad categories. The first includes low to medium bit rate services that can be processed by moderately advanced general purpose processors. Even their combined data throughput rates easily fit into one downstream QAM channel. Simple to moderately complex software programs are suitable to process the associated data streams.

The second group includes high bit rate services, such as digital video, which require large amounts of data to arrive at the home. They presently require dedicated processors to convert the digital data to the proper output format. Their data pipes occupy significant amounts of a downstream QAM channel.

Presently, cable companies install equipment for each individual service. This may not be a cost effective approach for the long term. An integrated solution results in improved spectrum management, easier network design, simpler maintenance and troubleshooting, fewer network management and operational support issues, and a much improved architecture for expansion [2].

Another important point is that a significant amount of end-terminal equipment requires cable company support to install and service. Deployment of set-top boxes and cable modem equipment requires a significant amount of support. The desire is to relegate the cable company to its original role of a service provider of analog or digital information over the cable.

Multi-service architectures at the home

There are several approaches to design multi-service architectures at the home. Reference [3] describes an integrated box at the side of the residence. A recent paper [2] proposed one with approaches based upon:

1) a digital selection and multiplexing of all downstream services in the headend,
2) remodulation of the QAM signals into Bipolar Phase Shift Keying (BPSK) signals in the home operating in the 930 MHz range,
3) BPSK for upstream signals in the home, also at 930 MHz, and
4) isolation between home wiring and HFC network to ensure network spectral integrity.

The Network Interface Unit (NIU) in this configuration passes the analog video signals and terminates the HFC plant with a tuner for the QAM receiver. It demultiplexes the incoming signal to feed the data, telephony, and digital video interfaces. The NIU becomes a "super box" with support for the most popular services. It may also require additional wiring between the outside box and the end-terminal devices inside the home, such as phones, set-top boxes, or PCs.

Service Type	Average Data Rate and Data Format	Packet Transfer Delay (Δt source - destination)	Packet Delay Variation	Packet Loss Effect	Error Handling
Digital Video	High (2-8 Mbps), MPEG-2 transport stream. (sometimes embedded in ATM.)	Moderately sensitive. Remote control commands must result in quick channel change.	Constant bit rate minimizes receiver buffer size.	Error concealment and correction possible to a certain extent.	Masking of errors by video and audio decoders.
Voice Telephony	Low (64 kbps), isochronous PCM data.	Very sensitive. Cannot tolerate large delays, otherwise requires echo cancellers.	Very sensitive.	Somewhat sensitive. Dropped data can be calculated from neighboring samples.	Simple interpolation routines.
Data	Variable data rates (100 kbps - Mbps), ATM packets.	Insensitive, as long as data streams not used for videoconferencing or voice calls.	Insensitive. Buffers are normally available.	Critically sensitive. Cannot tolerate missed data. Requires retransmission.	Application program runs error checking protocol.
Energy Management	Low (< 1 kbps.)	Insensitive.	Insensitive.	Sensitive	Error checking built-in in protocol.
Digital Audio	Medium (< 500 kbps), MPEG-2 transport stream, Dolby AC-3, etc.	Sensitive.	Sensitive.	Moderately sensitive.	Audio decoding process performs error masking.
Home Security and Automation	Low (< 1 kbps.)	Insensitive.	Insensitive.	Moderately sensitive.	Retransmission.
Video Conferencing	Medium (< 384 kbps), H320, H324, T.120 formats.	Very sensitive.	Somewhat sensitive. Normally sufficient amount of memory available.	Moderately sensitive. No retransmission for video and audio.	Video decoder can mask lost data. Quality of service is reduced.
Video-on-demand	(Similar to digital video.)	Moderately sensitive. Remote control commands must result in response.	Constant bit rate minimizes receiver buffer size.	Error concealment possible to a certain extend.	Masking of errors by video and audio decoders.
Internet Access	Medium (500 kbps - Mbps.)	Insensitive, as long as data path not used for video or audio playback.	Somewhat sensitive.	Sensitive. Requires retransmission.	Application program performs error checking.
Video Game Delivery	Low.	Insensitive.	Insensitive.	Sensitive. Cannot tolerate erroneous data.	Retransmission.

Table 1. Different Service Requirements over Cable.

There are some inherent limitations associated with this architecture. It deploys a single tuner in the NIU for all downstream signals. It forces the multiplexing of all requested services. This approach is probably not a problem for the low data rate services, but it causes problems for high data rate services such as digital video. Suppose that 100 homes are watching the same digital video stream on their set-top box. Their NIU tuner tunes to the same frequency. Suppose now that out of this group ten homes have a second set-top box required to be tuned to ten distinct digital video streams. Suddenly, the bandwidth is not there to multiplex eleven digital streams into one QAM channel. This shortcoming multiplies with an increasing number of services and homes on-line.

Other limitations of the NIU supporting multiple services are (1) the difficulty of powering a complex NIU through the cable network; (2) limited expansion capability for new or updated services; (3) sometimes proprietary modulation schemes incompatible with end-terminal devices; and (4) sooner or later the NIU will not have enough resources to support the plethora of requested services, especially high-speed video streams.

A NEW MULTI-SERVICE ARCHITECTURE AT THE HOME

The earlier attempts of integrated architectures made significant strides towards sharing of cable plant modem components. The combined tuner and QAM demodulator, and one upstream QPSK modulator, result in a significant cost saving for the deployment of multiple services.

The proposed architecture follows the same basic principle of sharing cable plant modem components, but distinguishes itself in several important ways. It still deploys an NIU at the side of the home, but it contains an inexpensive (bi-directional) modem operating in a narrow band in the 5-40 MHz range as an additional feature. This modem supports the Universal Serial Bus (USB) [4] protocol. The USB is a bus originally designed for the Personal Computer (PC) environment.

A Cable Termination Node (CTN), which consists of a similar modem with several standard Universal Serial Bus ports connected to end-terminal functions (telephone, speakers, PC, etc.), is placed at the end of the in-home cable. The CTN is basically a Universal Serial Bus (USB) hub with an upstream port modified for the coax cable.

Figure 1 shows a block diagram of the NIU. The main hardware characteristics are:

1) Simple NIU with minimum amount of hardware, fit to be powered by the cable plant, and independent of any particular cable service.
2) It terminates the HFC plant with a tuner for the QAM receiver in the downstream direction, but also passes a complete (buffered, amplified) downstream signal carrying the analog AM-VSB channels as well as all digital data channels into the home.
3) The NIU is responsible for remodulation of all services, except the high-speed ones, onto the in-home cabling in the downstream direction.
4) The NIU is responsible for remodulation of all services between the in-home cabling and headend using QPSK or QAM-16.
5) The NIU functions as a master device to in-home devices through a bi-directional link in the 5-40 MHz band deploying a standard Universal Serial Bus protocol.

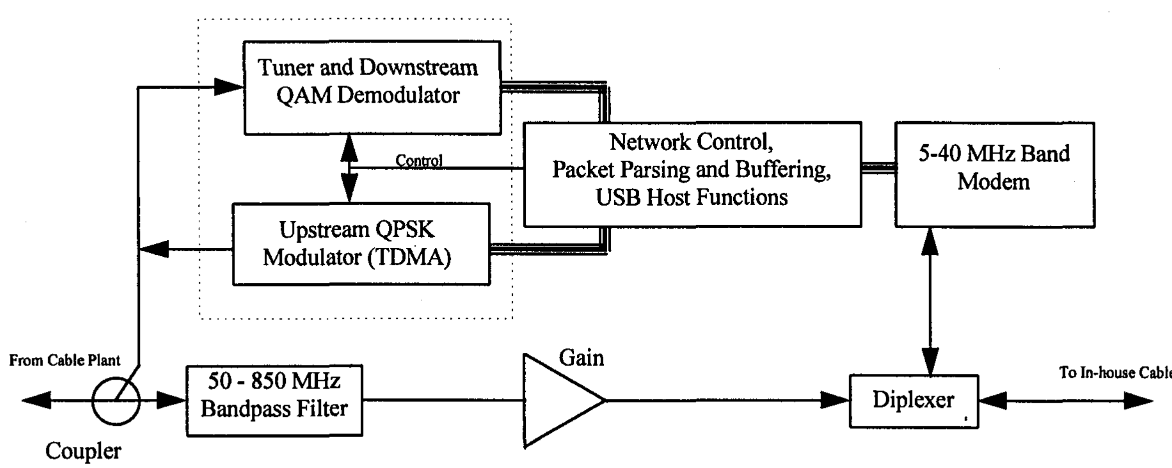

Figure 1. Network Interface Unit (NIU).

The following sections explain in more detail the reasons and justifications for the proposed architecture, and the NIU and CTN implementation.

Simple hardware implementation.

One of the objectives of this architecture is to make the NIU hardware independent of any of the possible offered services. A direct benefit of this choice is its simplicity and the associated low power requirements. The intention is to keep the NIU independent of any service, but use downloadable software programs to "customize" the NIU. The NIU QAM demodulator receives the low speed data services. The host microprocessor in the NIU forms the interface between the modem connection to the cable plant and the modem connection to the in-home cable. It functions as a USB host controller to the in-home network. A small integrated RISC processor handles the required processing load.

The simplicity of the NIU and the limited number of standard connections make it possible to install the NIU under ground level to protect it from weather extremes. Regular access to the NIU after installation is not required.

Buffered by-pass path.

The advantage of the high-speed by-pass path is that multiple set-top boxes (or digital TVs in the near future), each with their own tuner and QAM receiver, can be used in a residence. The headend does not require to perform any multiplexing of high-speed video streams for a particular residence. Another advantage is that future (high-speed) services can enter the home. The NIU does not prevent the downstream data flow from entering the home in any way.

Remodulation of all low-speed downstream services.

The motivation behind the selection of the USB for the cable environment is similar to the one for the PC environment. The intention is that the standard interface encourages consumers to use standard USB devices and connect them to the in-home cable without fear that the standard will become obsolete or will lose compatibility. It releases the cable companies from specifying end-terminal devices or maintaining them.

Some of the criteria for the definition of the Universal Serial Bus, which focuses on computer telephony integration (CTI), consumer, and productivity applications, certainly apply also to the in-home cable network:

1) Ease of use for peripheral expansion.
2) Low-cost solution that supports transfer rates up to 12 Mbps.
3) Full support for real-time voice, audio, and compressed video.
4) Protocol flexibility for mixed-mode isochronous data and asynchronous messaging.

Remodulation of all upstream services.

Communication between the NIU and the headend uses a QPSK or QAM-16 modulation scheme. The headend only needs to control ranging and power level management with respect to this transmitter and not with in-home devices. The NIU isolates the cable plant from the in-home network.

The NIU functions as a host USB Controller.

The Universal Serial Bus is a cable bus that supports data exchange between a host computer and a wide range of simultaneously accessible peripheral devices. The host uses a token based protocol to share the available bandwidth with up to 127 devices. The PC normally functions as the USB host. In the cable environment, the NIU takes over this function. There is only one host on any USB system, which may be implemented in any combination of hardware, firmware, or software. The NIU is very well suited for this function.

The function of the host is executed through the host controller. It detects the attachment and removal of USB devices to the cable, manages control flow between the host and USB devices, and collects status information. Unlike in the PC environment whereby the host provides a limited amount of power to attached USB devices, the NIU does not provided any power through the coax cable to any attached CTNs.

The Cable Termination Node (CTN).

The Cable Termination Node (CTN) is required in order to modulate and demodulate the narrow band signal in the 5-40 MHz band to a standard USB signal. The CTN functions as a generic USB hub with several downstream USB ports, but with the distinction that the upstream port is remodulated for coax cable transmission.

Figure 2 shows a block diagram of the CTN. The CTN consists of a standard USB controller chip, a USB driver chip, and a power management section in addition to the interface to the coax cable, formed by a modem identical to the one found in the NIU.

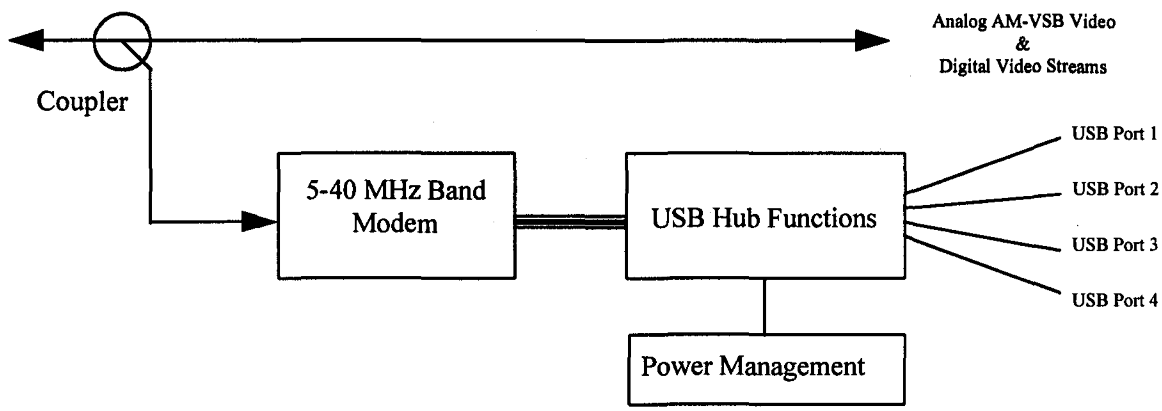

Figure 2. Cable Termination Node with Four USB Port Interfaces.

The CTN is a self-powered hub, i.e., it has a local power supply that furnishes power to any embedded functions and to all downstream ports. The disadvantage of this arrangement is that the NIU has no visibility of the hub when the CTN's power supply is off. It is therefore not possible to differentiate between a disconnected and an unpowered CTN. The NIU assumes that an unpowered device is a disconnected device. An analog path in the downstream direction guarantees that analog AM-VSB signals and QAM digital signals can bypass the CTN. The CTN is small enough to make it fit inside a standard cable outlet box.

USB OVER IN-HOUSE CABLE ISSUES.

The adoption of the Universal Serial Bus for the in-home network applies an existing bus and protocol to a new transport medium. Other in-home buses, such as the Consumer Electronics (CE) bus, cannot meet the requirements for the desired data rates over the in-home coax network. As these buses develop an interface to the USB serial bus, they can be interfaced to the proposed network.

The USB system describes three areas: (1) USB host; (2) USB devices; and (3) USB interconnect. The NIU performs the function of a USB host. The USB devices are divided in hubs and functions. A hub provides additional attachment points for the USB. Installation of USB devices for the cable environment should be as straightforward as in the PC environment: they attach to a CTN inside the home and will be recognized first by the attached CTN and then by the NIU.

The USB physical interface is based upon a four wire cable with two wires for power and ground, and the remaining two wires for signaling over point-to-point segments. The cable carries +5V on each segment to deliver power to devices. The USB specification limits the maximum cable length to several meters in order to meet IR drop specifications and guaranteed input voltage levels. The signals on each segment are differentially driven.

The proposed architecture requires a modification of the USB physical interface between the NIU and the CTNs. The standard physical output of the NIU is a coax cable entering the home. This cable may split several times before terminating in several rooms.

The Universal Serial Bus is a standard bus defined for the Personal Computer environment. The PC, as the host, uses several ports to communicate to hubs or functions. There is only one physical cable entering the home with passive taps going to multiple endpoints. The USB specification describes the bus attributes, protocol, types of transactions, bus management, and the programming interface to design and build systems and peripherals that are compliant with this standard. An extension to a different physical medium, such as the coax cable, requires some modifications.

The protocol relies on differential signals to indicate bus states and device conditions. We do not recommend duplication of these (DC) signals on the in-home coax cable due to the likelihood that a DC path may not exist. The NIU can circumvent these issues by interrogating from time to time all attached CTNs.

The USB specification defines two different data rates: a high-speed one at 12 Mbps and a low-speed one at 1.5 Mbps. Support of the low-speed data rate is not required in the cable environment since the NIU only communicates directly with the CTNs functioning as generic hubs attached to the end of the in-home cable.

Modulation scheme for the in-home network.

The in-home network must implement the Universal Serial Bus protocol over the coax cable. The required maximum data rate is 12 Mbps. The most suitable band available is between 5 and 40 MHz. The use of other bands, mainly above the analog video bands and above the digital QAM channels, would require expensive modulation and demodulation stages in the receivers and transmitters. What we are looking for is an implementation that is suitable for low-power CMOS ASICs.

Traditional modulation schemes come to mind. An implementation is possible with FSK, or BPSK, but these are expensive in bandwidth. For the requested data rate, the BPSK modulation scheme requires at least 15 MHz of bandwidth, thereby almost absorbing all the available bandwidth. QPSK is less demanding in bandwidth. Using direct-digital-synthesis, it is possible to implement transmitters in single chip CMOS circuits. QPSK receivers are more complex, requiring an analog-to-digital converter and some digital signal processing.

A recently proposed modem modulation method called INTRA (INformation TRAnsformation) is based on wavelet theory and the principles employed in multi-rate quadrature mirror filter banks (QMFs) [5,6]. Wavelet functions are functions that are localized in frequency and time. This method achieves data rates comparable to QAM data rates, but can easily be implemented in standard CMOS circuitry without the need for analog-to-digital converters or complex digital signal processing. The required bandwidth is also comparable to QAM.

The INTRA transmitter consists of a shift register and a ROM look-up table. The ROM stores the values for the wavelets, i.e., the short bursts of RF energy. A high-speed digital-to-analog converter converts the ROM digital output to the analog domain. The semiconductor industry has shown with QPSK modulator chips that it can implement high-speed digital circuitry and a digital-to-analog converter on a single die. The INTRA transmitter requires even less circuitry than QPSK transmitters.

Matched transversal digital filters receive the transmitted orthogonal wavelets. Since the wavelets are orthogonal, there is no inter-symbol interference. The receiver correlates the received waveform with the known waveform shapes. The simplicity of the INTRA receiver makes it also attractive for the in-home modem.

The NIU may also output the INTRA signaling over twisted pair wires as an alternate to the coax cable. It allows home owners to hook-up USB devices through the CTNs using less expensive wiring or to add additional wiring.

Software and cable applets (capplets).

The NIU and CTN require a certain amount of software in order to operate a service independent architecture as much as possible. The CTNs inside the house perform a function similar to a standard USB hub. Presently, there are small USB hub controllers available from multiple vendors that implement this function. The expectation is that these controllers will find a place in the CTN without many modifications to the existing software.

The NIU performs the function of a USB host controller and requires software to support this function. The attachment of USB devices in the home triggers the NIU with a request for acknowledgment of the function and possible additional software support in the form of a device driver or application program. A request to the headend by the NIU for support of the new USB function results in the download of a so called cable applet, or capplet for short. This capplet orchestrates, in cooperation with the embedded USB host software, the proper operation of the attached device. Its function is to transforms the downloaded data stream into a usable format for the device.

SUMMARY

This paper has suggested a new architecture for an integrated multi-service cable communications system. The Network Interface Unit (NIU) at the side of the customer premises functions as a Universal Serial Bus (USB) host device to support present and future end-terminal devices inside the home. The architecture allows for integration of future services through the support of the popular USB bus. All the USB devices available to the PC environment, become available to use as attachments to the cable.

The NIU communicates to the headend similar to a traditional cable terminal device using QAM demodulation in the downstream direction and QPSK modulation in the upstream direction. It communicates with the in-home Cable Termination Nodes (CTNs) using the Universal Serial Bus protocol modified for the in-home cable environment. This paper proposes to use a wavelet based modulation scheme, called INTRA, between the NIU and each CTN as an inexpensive and robust in-home modem.

The architecture isolates the in-home network from the outside cable plant. An added benefit of the achitecture is that it greatly simplifies cable plant design, and reduces maintenance.

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