# Broadband Access Using Subcarrier Multiplexing and Asymmetric Digital Subscriber Lines

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#### Abstract:

A broadband access system using subcarrier multiplexing on the optical fiber and asymmetric digital subscriber lines (ADSL) on unshielded twisted-pairs is proposed to deliver broadband services. In this hybrid-fiber/twisted-pair (HFTP) system, the digital multiplexing/demultiplexing process is moved back to the central office by using subcarrier multiplexing for fiber transmission. Instead of installing in remote node, ADSL transceivers are installed inside the central office to greatly reduce the remote node complexity. The local node simply down-converts the subcarrier multiplexed ADSL signal to baseband signal, suitable to send directly into the twisted-pair. The reducing of complexity could result in a lower initial installation cost, especially for a low service penetration rate.

#### 1. Introduction

As World Wide Web becomes the dominate application in the Internet<sup>1</sup>, more and more bandwidth intense multimedia content is requested by home users. In addition, the communication and entertainment industries would like to provide broadband services to the home. In addition to plain old telephone service (POTS) that carries voice signals to almost every household, those services build upon the ability to transmit multimedia content using modern communication technologies. Those broadband services include high-speed Internet access, tele-commuting, tele-retailing, video dial tone, video library, etc.

A broadband trunking and switching network and high-speed subscriber lines are essential to support these services. The broadband trunking and switching network between switching offices can be supported by asynchronous transfer mode (ATM) switching and high-speed synchronous optical networks (SONET). One way to build the subscriber loop is to bring fiber all the way to the home. Fiberto-the-home (FTTH) has long held the promise of being the ultimate vehicle for the delivery of broadband services. However, in spite of significant industry effort that has produced dramatic reduction in the cost of fiber and related components, there remain serious near term barriers in cost, standards, and technologies to the widespread installation of dedicated fiber to each subscriber residence. There are several different alternatives for the high-speed subscriber loop, most of them depend on fiber-optic feeder and either coaxial or twisted pair distribution subscriber networks<sup>[1]-[2]</sup>. In this paper, we propose a new fiber-in-the-loop (FITL) architecture that combines the advantages of those alternatives.

Some cable television (CATV) operators have used hybrid fiber/coaxial cable (HFC) architecture by installing fiber links to improve system reliability<sup>[3]</sup>. Fiber is employed from the switching office to local node to support a neighborhood cluster of 200 to 2000 homes. The fiber terminates in a local node with optical-to-electrical converter, from where coaxial cable carries the signal to the homes. The fibers carry an AM-VSB signal, intensity-modulated onto the optical carrier<sup>[4]</sup>, to a local node and no complex signal-format conversion is required there. The conventional tree-structured coaxial cable network then carries signals over the distances between the local node and the home. Because the fiber carries the CATV signal used by the cable television industry employing subcarrier-multiplexed techniques, in general, the signals arriving at the home are essentially the same as those leaving the switching office. Digital television can be supported by digital modulation on some subcarriers. Limited broadband services, called cable modem, can be supported by inserting the required channels onto empty channel slots. Currently, the HFC system is the most economic method to provide broadcast television service to the home, especially for the CATV industry with a large number of existing coaxial cable distribution networks.

<sup>1.</sup> For the statistics for the number of domain names, refer to http://www.nw.com

A technology using digital transmission aimed at supporting high-speed Internet access and multimedia transmission is the asymmetric digital subscriber line (ADSL)<sup>[5]</sup>. The key idea of ADSL, as the term asymmetric suggests, is to transmit the high-speed data stream only in one direction: from central office to the home. The ADSL can be implemented in either carrierless phase and amplitude (CAP)<sup>[6]</sup> or discrete multitone (DMT)<sup>[7]</sup> modulation format. ADSL uses the existing twisted pair wiring, depending on distance, to deliver high-speed downstream data from 1.5 to 6.4 Mb/s and upstream data from 128 kb/s to 640 kb/s<sup>[8]</sup>.

The fiber-to-the-curb (FTTC) architecture uses optical fiber transmission to curb-side Optical Network Units (ONUs). Several FTTC architectures have been considered including one which deliver baseband video over unshielded telephone twisted pairs to the subscriber homes. While fiber is used from the central office to the ONU, a Very-highspeed Digital Subscriber Line (VDSL) with a downstream transmission throughput of between 13 to 52 Mb/s<sup>[9][10]</sup> can be used for the twisted pair connection for the shorter distance.

In the FTTC system, ADSL or VDSL modems are designed to be installed inside the curbside remote node. Depending on the modem throughput and number of subscribers, a remote node requires to support an OC-12 rate, i.e. 622 Mb/s, for about 100 users of 6 Mb/s ADSL or 12 users of 52 Mb/s VDSL. Signal conversion and processing is taking place in each remote node. Depending on the final destination, signals are demultiplexed and modulated to ADSL modems. The demultiplexing from 622 Mb/s digital data and routing to 12 or 100 different output ports is not a trivial task. Similarly, for the upstream traffic, all digital sources from different subscribers must be first multiplexed together and transmitted to the central office.

The primary advantage of subcarrier multiplexing in HFC systems is that no signal conversion or very simple signal conversion is required in the remote node. A Hybrid Fiber/Twisted-Pair (HFTP) system, shown in Fig. 1, has very simple signal conversion requirements in the remote nodes. The topographical layout of the HFTP system is identical to a remote node deployed ADSL system or a FTTC system. However, instead of using digital signals in the optical fiber, subcarrier multiplexing is employed to transmit ADSL signals in different subcarrier channels. The HFTP system primarily provides a transparent ADSL "pipe" from the central office to the subscriber home. The HFTP architecture combines the advantage of HFC systems for using subcarrier multiplexing and the advantage of ADSL systems for accommodating the existing twisted pairs. The employment of subcarrier multiplexing with bandwidth efficient DMT and CAP modulation in each subcarrier also increases the number of channels (or capacity) of the optical fiber.

Because most expensive equipments are installed in the central office instead of local nodes, a HFTP system is less expensive for installation, maintenance, operation, and management.

## 2. Architecture of Hybrid Fiber/Twisted-Pair Systems

Fig. 1(a) shows the network architecture of the HFTP system. The central offices are linked together by SONET using ATM switches. The conventional POTS and broadband service (data and video) can be supported by the same SONET or different SONET networks. Similar to HFC and ADSL based FTTC systems, optical fibers are employed from the central office to local nodes. Subcarrier multiplexing is used in the optical fiber by sending the ADSL signal to different subscribers on subcarrier channels at different frequencies. The typical spectrum in the optical fiber is shown in Fig. 1(b), which is similar to the spectrum utilization of an HFC system. At the remote node, an optical network unit (ONU) converts the optical signal to electrical signal. The subcarrier multiplexed signal is down-converted to a baseband ADSL signal and directly sent to the twisted pair. In the residence home, the Network Interface Unit (NIU) is basically an ADSL modem. The ONU also up-converts the upstream signals to different subcarrier frequencies. The same fiber can be employed using either subcarrier multiplexing at higher frequencies (see Fig. 1(b)) or wavelength division multiplexing using different wavelengths







for upstream and downstream signals. Alternativelý, separated fibers can be employed for the upstream and downstream signal.

Fig. 2(a) shows the block diagram of the system at the central office. Assume that MPEG video or data services come from a single SONET facility that links all central offices. The customer payloads are first added/dropped from the SONET. The received payloads (the downstream data) are demultiplexed and routed to the corresponding ADSL modem. Similarly, the upstream data need to be multiplexed together and added to the outgoing SONET facilities. Following the ATM add/drop and mutiplexing/demultiplexing functionality is an ADSL modem bank and subcarrier modulator/ demodulator bank. The functionality of the ADSL modem bank and subcarrier modulator/ bank is shown in Fig. 2(b).

At the ADSL bank, for the downstream data, an ADSL modem is first employed to generate the baseband modulation<sup>2</sup> of the ADSL signal. Because the transmit system from the central office to the residence is a transparent pipe for the ADSL signal, either carrierless amplitude and phase (CAP)<sup>[6]</sup> or discrete multitone (DMT)<sup>[7]</sup> baseband modulation format can be employed. The subcarrier modulator/ demodulator bank consists of basically up-converters and down-converters. The subcarrier ADSL signals to different subscriber homes are up-converted to different subcarrier frequencies. A combiner combines all subcarrier multiplexed ADSL signals and the combined signal is used to drive a subcarrier multiplexing optical transmitter which is similar to the transmitter of an HFC system, but potentially much cheaper. For the upstream signal, the received subcarrier multiplexed signal is down-converted to baseband signal and received by an ADSL modem. Similar to the downstream data, all CAP or DMT modulation formats can be employed for the upstream data.

Fig. 3(a) shows the block diagram of the ONU in local node. An optical/electrical converter receives the subcarrier multiplexed signal from the central office, followed by a subcarrier modulator/ demodulator bank and ADSL driver bank. Fig. 3(b) shows the functions of the subcarrier modulator/ demodulator and ADSL driver banks. Downstream signals at different subcarrier channels are downconverted to baseband ADSL signals. Upstream signals from different subscribers are up-converted to



Fig. 2 (a) Block diagram at the central office for the signal transmitted to and received from each local node. (b) Functional diagram of the subcarrier modulator/demodulator bank.



Fig. 3 (a) Block diagram at the local node. (b) Functioning diagram of the subcarrier modulator/demodulator.

<sup>2.</sup> The ADSL modem can also generate the signal at an intermediate frequency (IF) such that the following up-conversion can be more easily be processed.

different subcarrier frequencies. The ADSL driver is basically a simple interface between the twisted pair and O/E and need only provide filtering, impedance matching, and isolation for the forward and reverse signals. We assume that the upstream and downstream channel in the twisted pair use different frequency bands such that no echo cancellation is required. Conventional POTS can be provided by inserting the signal at the ADSL driver through a splitter.

The ONU in the remote node of an HFTP system is simpler than the Remote Digital Terminal (RDT) in a conventional FTTC system. ADSL modems and complicated demultiplexing and routing equipment are located in the central office instead of curbside plant. The HFTP ONU is smaller, simpler, and cheaper, and also easier to install and maintain. In addition, the central office is a better, more controlled environment than the outside plant to place the demultiplexing and modulation electronics, potentially saving costs on installation, maintenance, operation, and network management.

Both HFC and HFTP systems use subcarrier multiplexing from the central office to the local node. Therefore, identical equipments can be used for both systems. Many subcarrier multiplexing systems are already in service. It may be possible to build upon the successful development and deployment of these systems to feed twisted pairs, already in place in the telephone plant. However, as shown later, preliminary analysis indicates that the HFTP system does not require a high-performance linear laser transmitter like HFC systems, resulting in potentially lower cost systems. HFC and HFTP systems can co-exist; for example, some of the subchannels carry conventional analog or digital HFC signals and others carry ADSL signals. In the local node, both coaxial cable and twisted pairs can be used to send signals to the subscribers. The combined HFC/HFTP system can accommodate the existing coaxial cable and twisted-pair of both the local CATV company and telephone company.

In subcarrier multiplexing systems, laser nonlinearity can induce distortion to the system. Most subcarrier multiplexed transmitters use linear DFB lasers or linearized external modulators, such that all HFC transmitters can deliver video signal with composite second order (CSO) and composite triple beat (CTB) distortions less than -65 dBc. At the same time, the carrier-to-noise ratio (CNR) of these systems is greater than 55 dB. Existing HFC equipment is shown to be quite adequate for HFTP system. However, existing HFC equipments may be overengineered for the HFTP application. As shown below, the HFTP system does not require a CNR as large as 55 dB and the linearity requirement of HFTP systems can also be reduced due to the small CNR requirement. This may result in potentially lower cost systems.

The throughput of the HFTP system is limited mainly by the twist-pair length and the available bandwidth. Numerical results show that for a bandwidth of 6 MHz, a data rate of more than 20 Mb/s can be achieved for a twisted-pair length up to 5 kft for an optical CNR of 40 dB.

Higher throughput can be achieved by reducing the twisted-pair length or increasing the optical receiver CNR. While an optical receiver CNR of infinity can not be achieved, an optical receiver CNR of 30 and 40 dB may induce a throughput reduction of 20 to 40% and 10 to 15%, respectively.

### 3. Comparison of HFTP and FTTC

For a comparison, we assume that the HFTP system employs a transmitter and receiver having a bandwidth of 600 MHz and the FTTC system uses an OC-12 link with a data rate of 622 Mb/s, a down-stream data rate of 20 Mb/s and upstream data rate of 1.5 Mb/s are used for each subscriber. The FTTC system can support about 30 subscribers per node. The HFTP system may support 100 subscribers with 20 Mb/s within each of the 6 MHz bandwidth. If the HFTP system only requires to support 30 subscribers, less than 180 MHz bandwidth is required. The OC-48 data rate is required for the FTTC system to support 100 subscribers.

Usually, because of high CNR requirement and small modulation index, subcarrier multiplexing for analog transmission costs more than baseband onoff keying digital transmission. More optical power must be received in the HFTP system to achieve comparable performance to the FTTC system. However, three times more subscribers can be supported by a HFTP link with the same bandwidth as a FTTC system. If the HFTP system requires to support the same number of subscribers as the FTTC system, the required bandwidth is about three-time smaller than the corresponding FTTC system. The smaller bandwidth requirement will result in lower laser cost. If the FTTC system wants to support a comparable number of subscribers of the HFTP system using the OC-48 data rate, the cost and complexity of the FTTC system will increase. For example, both in small quantity, the cheapest AM-VSB transmitter and receiver pair with 750 MHz bandwidth and CNR larger than 50 dB cost about US\$5,000 but an OC-48 transmitter and receiver pair costs about US\$8,000 or even more.

The HFTP system can use HFC equipments or co-exist with an HFC system. However, most HFC transmitters have a large output power and can transmit over a long distance. If we want to focus on the FTTC applications, the distance from the central office to remote node is around 12 kft and corresponds to a loss budget of less than 2 dB in the 1550 nm wavelength window.

Usually, an optical receiver power of about 0 dB is required to achieve an optical CNR of 55 dB. Optical transmitter of AM-VSB system has an output power of at least several dBm. If an optical receiver CNR of about 40 dB is required, the required received optical power is about -7 dBm. Taking into account the 2 dB loss budget, a transmitter power of less than -5 dBm is required. A laser transmitter having a power of -5 dBm is significantly less expensive than a laser transmitter having an output power of several dBm. Combined with the low linearity requirement, an HFTP transmitter should be less expensive than an HFC transmitter. While an HFC transmitter currently costs about \$5,000 (for about +5~6 dBm output power), an HFTP transmitter may cost as low as \$1000.

As mentioned earlier, a big advantage of HFTP systems is simple installation, maintenance, network management and operation. All critical and expensive equipments, including ADSL modems, ATM demultiplexer, and ATM cell router, are located in the central office. In contrast, in the FTTC system, these equipments are located in the curbside node. The local node of an HFTP system consists of simple signal up-conversion or down-conversion circuitry.

## 4. Comparison of HFTP and HFC

Analog broadcast television can be supported by HFC systems. Only compressed digital video can be transmitted in FTTC and HFTP system and this represents a significant advantage for the HFC system. However, medium access control (MAC) is a difficult problem for upstream data because of the broadcast nature of the HFC system. Because subcarrier multiplexing is employed in the fiber portion of both systems, HFTP and HFC systems can use the same kind of equipments or even co-exist. However, as shown later, a high-performance HFC transmitter is not required in HFTP systems.

An HFC system can support 200-2000 subscribers from a local node because of the broadcasting

nature of the network. A single transmitter can support several local nodes by splitting the optical power. Depending on the data rate of each subscriber, an HFTP system can only support 50-600 subscribers from a local node. In general, on a persubscriber basis, the HFC system is less expensive than the HFTP system. However, the services provided by HFC and HFTP system are different. The HFC system is basically a broadcasting network and the HFTP system provides dedicated one-to-one persubscriber communication links. For a fair comparison, both system must be compared when supporting similar services.

If HFC systems support two-way communications, the number of subscribers supported by each transmitter must be decreased. If all subscribers want to have the video-on-demand service, a channel must be assigned to each subscriber such that each subscriber can choose his or her own program. For a system with 600 MHz bandwidth, an HFC transmitter may support around 500 subscribers for a 500 channel system in which each channel transmits 6 Mb/s MPEG-2 video using 64-QAM modulation. For this full video-on-demand service, the HFC system and the HFTP system can support an identical number of channels and identical number of subscribers per transmitter.

Currently, an HFC transmitter is expensive because a super-linear DFB laser or linearized external modulator is required. However, as shown earlier, unlike the 55 dB CNR requirement of an HFC system, an HFTP system requires a CNR of about 40 dB. We expect that uncooled Fabry-Perot lasers can be used in HFTP applications, especially for the upstream data with 1.5 Mb/s QPSK modulation format.

## 5. Summary

An HFTP system is proposed here for broadband services distribution. The main advantage of the HFTP system is to put all critical and expensive equipments in the central office, reducing the cost of installation, maintenance, operation, and network management.

The HFTP system has the same topographical layout as a remote node deployed ADSL or FTTC system. In contrast to the current ADSL and FTTC provisioning approaches, the digital multiplexing/ demultiplexing process has been moved back to the central office. Subcarrier multiplexing is employed in the optical fiber, and the local node just downconverts the subcarrier multiplexed ADSL signal to a baseband signal suitable for twisted-pair. It is expected that the complexity of the local node can be reduced. This could result in a lower initial installation cost, especially for a low service penetration rate.

#### 6. References

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