CHAPTER 17.4
BROADBAND SYSTEMS

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Broadband systems refer in general to Broadband Integrated Services Digital Network (B-ISDN), which provides user access at a speed over the T1 rate (1.5 Mb/s). Integrated Services Digital Networks are defined to be networks that provide end-to-end digital connectivity to support a wide range of services, including voice and nonvoice services. Nonvoice services include image and video, as well as high-speed data transmission. B-ISDN allows the traditional interactive computer applications to run at higher speeds and enables the development of innovative distributed applications using computing and storage resources distributed over the network. It also enables new applications that were not possible because of bandwidth limitations, such as distribution or broadcasting of digital video information.

The concept of ISDN began to emerge in the 1970s, and the set of international standards were issued in the early 1980s by the ITU-T (formerly CCITT). The initial ISDN consists of multiples of fixed 64 kb/s channels, up to a total of 1.5/2.0 Mb/s. Subsequently, the idea of integrated services was extended to broadband networks, such as Synchronous Optical Network (SONET) at a speed of 155 Mb/s or higher, and was named Broadband ISDN (B-ISDN) to contrast it with the original lower bandwidth ISDN. In this section the term ISDN (without the B prefix) refers to the narrowband ISDN.

In addition to the speed difference, ISDN uses synchronous time division multiplexing for 64 kb/s channels, while B-ISDN uses an asynchronous fast packet switching technique called Asynchronous Transfer Mode (ATM) in which data channels are identified by a virtual path/virtual channel identifier in each packet. The size of the packets is fixed and small; the packets are called ATM cells.

This section first introduces the basic concepts of narrowband ISDN, then covers the physical interfaces and services of broadband ISDN.

THE NARROWBAND ISDN

From a telephone user's perspective, there have been very few changes in the way a telephone set works ever since it was invested. The few major evolutions include powering from the central offices, automatic switching, and tone dialing. The underlying telecommunications network, however, has gone through major changes such as digitalization of transmission facilities and development of intelligent network architecture. ISDN provides a revolutionary change of the capability and functionality of telephone sets. The definition given above shows several unique characteristics of ISDN: (1) It allows end-to-end digital connections by providing digital access on the local subscribers loop from the customer's premises to the central office; (2) it provides an integrated service by carrying voice and nonvoice data, including text, image, and motion video, over a single physical interface. In addition, it also provides a signaling channel separate from the user's data channels, permitting access to advanced features of an intelligent network.

Digital Access to Customer Premises

Over the years, the public telephone network has evolved from an analog transmission network into a digital network. Most of the central offices use digital switching, and trunk lines employ digital transmission facilities. The link from the central office to the customers' premises, called the Local Subscribers Loop, however, remains analog. ISDN standards define two types of digital interfaces: the *Basic Rate Interface* (BRI) and the *Primary Rate Interface* (PRI). Each of them provides a signaling channel called the D channel, and a number of user data channels called B channels. The BRI D-channel can also carry limited user data.

The basic rate interface consists of two 64 kb/s B-channels and a 16-kb/s D-channel (2B+D). The B-channel uses 64 kb/s rate since that is the basic rate at which all analog voice signals are digitalized. The physical interface operates at a 192 kb/s rate, using time division multiplexing for the B and D channels and other overhead bits. The primary rate interface has two formats. One is based on the T1 (U.S.) digital hierarchy and the other is based on the E1 (European) digital hierarchy. The T1-based PRI consists of 23 B-channels and one D-channel (23B+D) while the E1 rate consists of 30B+D. The bandwidth of each B- or D-channel is 64 kb/s. The B-channels could be combined into multirate circuit mode ($N \times 64$) channels at increments of 64 kb/s. Some special rates are defined as H channels, for example, the H_0 channel at 384 kb/s, and the H_{10} channel at 1472 kb/s.

Out-of-Band Signaling

In the Plain Old Telephone System (POTS), the signaling between a user and the network for control of a connection is by means of on-off hook current levels and dialing pulses/tones in line with user data. In ISDN, a data link connection (based on Q.921) is established between a terminal and the central office switch on the D channel. Call control signals (based on Q.931) could be exchanged at any time, independent of the use of the data stream on the B channels. Call control information includes the called and calling numbers, bandwidth requirements and B-channel assignment, service request (voice or data, circuit or packet), end-to-end protocol selection, and so forth. Additional services could be invoked or provided, such as call redirect from the terminal, call waiting notification, conference call, or additional end-to-end-user data for call setup.

ISDN Services

Very often multiple phone lines are needed in an office, one for voice and one or more for data (using modems). ISDN enables multiple connections and services over a single physical interface. Not only can it provide high-speed connections at 64 kb/s, which are not possible with modems, it also allows multiple connections to be synchronized or coordinated. Instead of dedicating a phone line for a specific service, ISDN allows a greater freedom in the sharing of phone facilities. The bearer services, or the basic services to which users can subscribe to run their applications include circuit mode and packet mode services, as described below.

Circuit-Mode Data Service. This service provides an unrestricted channel so that the bit stream is passed unchanged end to end. The actual application is controlled by user equipment at each end and could thus, in principle, transport voice or data with necessary protocols such as X.25 or Frame Relay.

Circuit-Mode Speech and Voiceband Services. The Speech and Voiceband services carry voice signals as currently provided by POTS. The bit stream is assumed to be digitalized analog signals using appropriate encoding standards. Conversion may take place when passing through networks employing different encoding standards. The Voiceband service is for 3.1 kHz audio, which is used for modems.

Packet-Mode Data Service. This service allows access to the X.25 packet network service offered by the network to which the terminal is directly connected. From the users' perspective, the packet switching network is fully integrated with the circuit switching network. The service is available only on the BRI B and D channels.

BROADBAND ISDN AND ASYNCHRONOUS TRANSFER MODE NETWORKS

The concept of broadband ISDN was a logical extension of narrowband ISDN in the evolution of telecommunications networks. The standards development started in the late 1980s, and ITU-T reached its first agreement on general aspects of B-ISDN in 1988. While B-ISDN was originally developed as a telecommunications technology, it has been adapted for data communications as well. In particular, it has been used as a new Local Area Network (LAN) technology. The ATM Forum, an industry consortium, has speeded up the development and made major contributions in this area.

Since the major feature of B-ISDN is the use of ATM, the terms B-ISDN and ATM are used synonymously.

Asynchronous Transfer Mode Cell Switching

The use of ATM technology is a major paradigm shift from synchronous networks where user data are carried in fixed time slots in the transmission facilities. ATM uses an asynchronous time division multiplexing technique to carry information in fixed size ATM cells. An ATM cell consists of two fields: a payload field for user data and a header field for identification of the user channel. Cells are assigned to user channels on demand, therefore the bandwidth occupied by a given user may vary from zero to the capacity of the physical link.

The size of an ATM cell is 53 octets, the first five for the header and remaining 48 for the payload. The header, among other things, contains an 8-bit virtual path identifier (VPI), a 16-bit Virtual Channel Identifier (VCI), and an 8-bit Header Error Check (HEC). The switch simply relays the cells based on the VPI/VCI number. The HEC is needed to prevent misrouting. There is no error control for the cell payload. Error recovery must be performed by the end systems. All that is required of the network is the delivery of cells in their original sequence.

There are two types of connections: *Virtual Path Connection* (VPC) and *Virtual Channel Connection* (VCC). VPC is analogous to a big pipe which allows end points to do their own distribution and assignment of individual virtual channels. The network will route cells based on the VPI. The VCI is for individual connections in which the network will route cells based on the combined value of VPI/VCI.

Physical Layer

Since B-ISDN was developed for public telecommunications network, it is expected that the standard-based SONET and synchronous digital hierarchy interfaces will be the most important physical media for B-ISDN/ATM networks. For the OC-3 interface the SONET STS-3c synchronous payload envelope is continually filled with ATM cells, byte aligned. This gives an effective rate of about 150 Mb/s over the 155.52 Mb/s interface. The mapping for the OC-12 interface has also been defined.

Currently not all network transmission facilities are SONET based; the existing digital hierarchy, the DS3, DS1 (for the United States) and E3, E1 (for Europe) are also to be used for ATM interfaces. There are two ways to map ATM cells into the DS3 payload: the DS3 Physical Layer Convergence Protocol (PLCP) format and the direct mapping format. The PLCP frame consists of 12 rows of ATM cells, each preceded by 4 octets of overhead. At the end the frame is stuffed with a variable number of nibbles (4 bits) to fill up the 125 μs frame. The direct mapping format continuously fills the DS3 payload with ATM cells with nibble alignment.

For use in the LAN environment, other less expensive media have also been accepted. These include 155.52 Mb/s over Category 5 Unshielded or Shielded Twisted Pair (UTP and STP), 51.84 Mb/s over Category 3 UTP, and 25.6 and 25.2 Mb/s over various twisted pairs. Additional fiber formats could also be used; this includes 100 Mb/s over multimode fiber using the FDDI 4 bit/5 bit (4B/5B) code, and 155 Mb/s over multimode fiber using 8B/10B code.

Another important transmission medium for B-ISDN is the use of communications satellites. The subject is covered later.

B-ISDN Services

B-ISDN provides integrated services for voice, text, image, and video just like the narrowband ISDN, but at a wider range of bandwidth. Since B-ISDN uses packet mode for information transfer, it needs to simulate the services provided in the traditional circuit mode transfer. Therefore, cell transfer delay and delay variation become important service parameters. It is a major challenge for the service provider to take full advantage of statistical multiplexing while maintaining the desired level of quality of services.

Constant Bit Rate Service (CBR). This service is for applications that generate a stream of bits at a constant rate and have a real-time requirement, such as voice and video applications. These applications require tightly constrained cell transfer delay and delay variations.

Variable Bit Rate Service (VBR). This service supports applications that generate bursty traffic. Some applications may have real-time requirements, such as compressed voice and video applications. Other applications may be non-real-time but still require a bound on cell transfer delay.

Unspecified and Available Bit Rate Service (UBR and ABR). This service supports the traditional data communication applications, such as e-mail, file transfer, and interactive traffic. The source is expected to be bursty. The network provides the best effort delivery service, and may discard cells when congestion occurs. The ABR service requires a flow control mechanism that provides feedback to the source from the destination as well as from network nodes.

ATM Adaptation, Signaling, and Interworking Functions

ATM Adaptation. Because of the diversity of services that must be supported in a B-ISDN/ATM network, some type of interface must be provided between the ATM layer protocol and the applications on the end systems. The ATM adaptation layer (AAL) protocol was developed for this purpose as well as for the end-to-end error control, which is not provided by the ATM layer cell switching protocol. The major functions of AAL at the sender side include: (1) packing of user messages into AAL message(s) with insertion (when necessary) of sequence numbers, error protection (parity, CRC or FEC), clocking signal, and padding; (2) segmentation of messages into ATM cells and delivery for transmission of cells at the specified rate. The receiver side performs the reverse functions, including error checking of cells received, recovery of source clock and handling of cell transfer delay (for CBR traffic), reassembly and delivery of messages to the application, and notification of transmission errors. There are several types of AALs defined, each designed to meet the requirement of a particular service, for example, type 1 for CBR service and type 5 for ABR/UBR and some VBR services.

ATM Signaling. Since ATM is a connection-oriented protocol, a B-ISDN/ATM network must provide connection setup. The procedure uses the signaling protocol Q.2931, which is an extension of the one used for narrowband ISDN. During the call setup, the calling and called parties and the network must check or negotiate the relevant service parameters such as cell rate (peak, sustainable, minimum), cell transfer delay (mean, maximum, variation), and cell loss ratio, depending on the service requested.

Interworking with other Networks. The higher bandwidth of B-ISDN/ATM networks enable better use of applications involving multimedia and digital video. In addition to addressing new applications, we must still make these networks interwork seamlessly with existing POTS, ISDN, Frame Relay, LANs, and the Internet. One important issue is support of connectionless IP Internet in a connection-oriented ATM network. The LAN emulation service developed at the ATM forum and the adaption of Internet router functions to the ATM network are examples of solutions for interworking.

Satellite Links for B-ISDN/ATM Networks

As was mentioned earlier, the standard-based SONET and Synchronous Digital Hierarchy will be widely used for ATM. However, for regions not served with fiber, satellite communications can be used to provide the physical layer for B-ISDN/ATM networks. It is shown here that data rates of 155.52 Mb/s are possible using satellites and modems available today. It is shown that higher data rates could be supported but only in restricted cases.

TABLE 17.4.1 Modulation and Coding Performance for Various Modulation Types Used in Satellite Communications.*

Modulation (Coding Rate)	Eb/No dB	*Rb* dB* Mb/s	*Rb* Mb/s	BW MHz
QPSK(1/2)	9.0	84.6	288	374
QPSK(1/2,RS)	5.2	88.4	692	990
QPSK(3/4)	11.0	82.6	182	158
QPSK(3/4, RS)	6.5	87.1	512	488
8PSK(5/6)	12.0	81.6	146	76
8PSK(2/3, RS)	7.5	86.1	407	291
16 QAM(7/8, RS)	10.9	82.7	186	76

*For C band zone, Example: 8PSK(2/3,RS) is 8 phase shift keying with rate 2/3 inner code with Reed-Solomon outer code.

Link Budget. Link budgets, which are fundamental to satellite communications, were performed for both C and Ku band with INTELSAT satellite systems to determine the maximum practical data rate that could be supported with the Standard A antenna (15 m) for C band and the Standard C antenna (11 m) for Ku band. These link budgets yielded a system carrier to noise density C/No of about 93.6 dB*Hz for the C band zone beam with a saturated effective isotropic radiated power (e.i.r.p.) of 34 dBw and a system C/No of about 2 dB greater for the Ku spot beam with a saturated e.i.r.p. of 46 dBw. These links are operated several dB backoff to accommodate phase and amplitude modulation.

Supportable Data Rates. With these values of C/No, the maximum data rate supportable can be calculated. Table 17.4.1 gives typical values for a bit error rate (BER) = 10** (–11) when using the C band zone beam. The bit energy to noise density Eb/No values were taken from the EFData Corporation Modem manufacturer's literature and are based on measured values, but at lower data rates than are considered below. (It is reasoned that the modem performance is independent of data rate if all other parameters are equal.) Table 17.4.1 also gives the approximate required bandwidth to support the modulation and coding used. These modems use either a convolutional code with the Viterbi decoder or the concatenated code scheme with an outer code of the Reed-Solomon (of rate approximately 9/10) and an inner code of the convolutional type just mentioned. The bandwidth (BW) required is given by the formula:

$$\text{BW} = Rb^{*}(1/R)^{*}(1/f)^{*}1.3 \text{ Hz}$$

where Rb = data rate
R = inner code rate
f = modulation factor and is 2 for quadrature phase shifting keying (QPSK), 3 for 8 phase shift keying (8PSK), and 4 for 16 quadrature amplitude modulation (16 QAM)

if the Reed-Solomon (RS) outer code is used when BW is increased by 10 percent.

There are three commonly used data rates considered here: 44.736 Mb/s (DS-3), 155 Mb/s (OC-3), and 622 Mb/s (OC-12). These data rates are used in the ATM architecture. Using the modulations given in Table 17.4.1 above, Table 17.4.2 yields the required bandwidth for the three data rates mentioned.

From Table 17.4.2, it seems that the DS-3 can be supported on 36 MHz transponders only for 8PSK and 16 QAM modulation. A transponder with a bandwidth of about 43 MHz can support DS-3 using all combinations except QPSK(1/2) and QPSK(1/2,RS). Consulting Table 17.4.1 shows that a DS-3 link can be supported by any entry in the table, as far as the required Eb/No is concerned. If a 72 MHz bandwidth transponder is considered, then Table 17.4.2 shows that a DS-3 link can be supported by all modulation/coding combinations.

The OC-3 (155.5 Mb/s) rate can be supported on about an 81-MHz transponder using the 8PSK(5/6) as shown in Table 17.4.2. Table 17.4.1 shows that the maximum data rate supportable from the Eb/No viewpoint is about 146 Mb/s. If one has a C band zone 72-MHz transponder, available on INTELSAT, this combination of modulation, coding, and transponder bandwidth will give performance close to the goal of the target BER and is recommended for OC-3 transmission. Results using the Ku band zone with the Standard C terminal will yield improved performance because of the 2-dB link improvement.

TABLE 17.4.2 Bandwidth Required for Certain Data Rates and Modulation

Modulation (coding rate)	44.736 Mb/s DS-3 (BW, MHz)	155.5 Mb/s OC-3 (BW, MHz)	622 Mb/s OC-12 (BW, MHz)
QPSK(1/2)	58	202	809
QPSK(1.2, RS)	64	222	890
SPSK(3/4)	39	135	539
QPSK(3/4, RS)	43	149	593
8PSK(5/6)	23	81	324
8PSK(2/3, RS)	32	111	445
16QAM(7/8, RS)	18	64	150

Tables 17.4.1 and 17.4.2 show that there is no combination of modulation/coding and available transponders that will support the OC-12 data rate. However, Table 17.4.1 shows that the QPSK(1/2,RS) will support OC-12 from the required Eb/No viewpoint but requires a bandwidth of 890 MHz. This clearly presents a problem since the fixed satellite service bands are only 500 MHz wide. The only other parameter in this discussion is the size of the earth station required to support OC-12 in a transponder of wider bandwidth. For example, a transponder of 500 MHz would support 8PSK(2/3,RS) but requires an Eb/No of about 7.5 dB (see Table 17.4.1). This would require a C/No of about 98.8 dB*Hz, equivalent to an antenna at C band of about 26 m in diameter. This is clearly a very large antenna by today's standards.

The other main parameter on the satellite besides the transponder bandwidth is the downlink e.i.r.p. This parameter could be increased allowing for one of the higher order modulations to be used. A several dB increase in the downlink e.i.r.p. would allow for 16QAM(7/8,RS) to be used to support the OC-12 data rate but the bandwidth would still be larger than 150 MHz.

It has been shown that the maximum data rate that can be supported is about 155 Mb/s using what is available now and in the near future. The present designs of satellites do not permit the support of OC-12 (622-Mb/s) rate. If this rate is to be supported by commercial satellite links, then the satellites of the future must increase both their transponder power and bandwidth.