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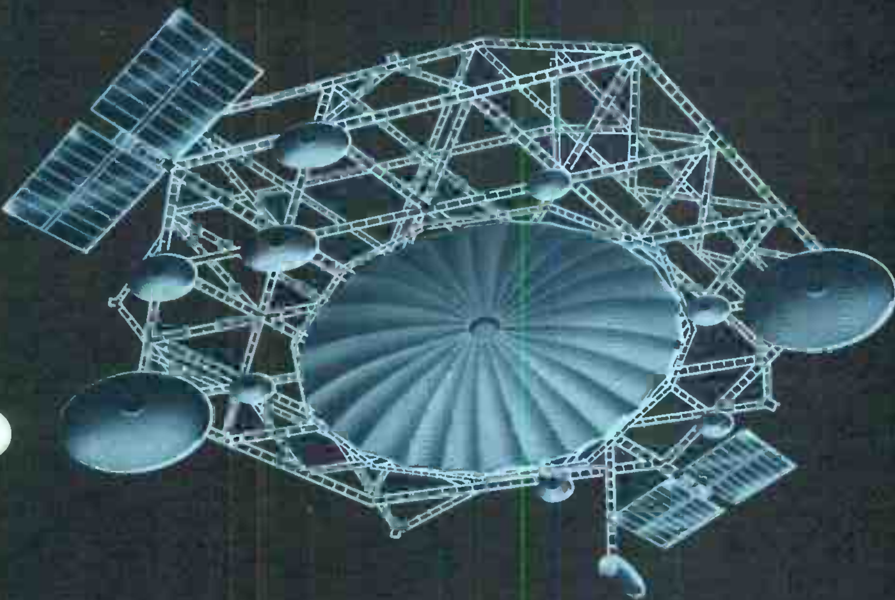

SATELLITE COMMUNICATIONS UPDATE part one

Also in this issue:
VLSI Codecs

The May 1962 and December 1966 issues of the Demodulator presented discussions of satellite communications. This issue briefly summarizes the information presented in the previous issues, to provide a background for describing what has occurred in the interval 1967 to the present. The last portion of this article mentions some highlights of future plans. These plans and earth stations will be described in the May issue.

The May 1962 Demodulator presents a detailed discussion of orbital mechanics. Some of the following information is extracted from that issue.

Orbital Velocity

To achieve orbit, a satellite must be lifted above the atmosphere and started moving around the earth at the exact speed required to produce a centrifugal force just equal and opposite to the gravitational force at that altitude. If the speed is too fast the satellite will tend to fly off into space. If the speed is too slow the satellite will be pulled back to earth by gravity. Figure 1 illustrates the principle of orbital velocity.

The earth's gravitational attraction decreases with altitude. Therefore, to overcome gravity, high altitude satellites do not have to circle the earth as rapidly as low altitude satellites. The time period required for each orbit is a function of the satellite altitude. Theoretically, the period also varies with the satellite's mass since gravity is proportional to the mass of the earth and the satellite. However, the satellite's mass can be neglected since it is insignificant in comparison to the earth's mass.

The required period for a circular orbit at a given altitude can be calculated from the formula

$$t^2 = \frac{a^3}{k}$$

where: a = altitude or distance from the earth's center of gravity

k = a constant

assuming the earth's radius as 4,000 miles and the altitude is in statute miles; then t is in minutes and $k = 8.9 \times 10^6$.

Figure 2 shows the velocities required to maintain an orbit at various altitudes and the time period for those orbits.

At an altitude of 22,270 miles, a satellite orbits the earth in exactly the same time period as the earth's rotation — just under 24 hours. Such a satellite is called an geosynchronous satellite because its orbit is synchronized to the earth's rotation. A synchronized satellite, placed in orbit directly above the equator on an eastward heading, appears to be stationary in the sky so its orbit is sometimes referred to as the geostationary orbit.

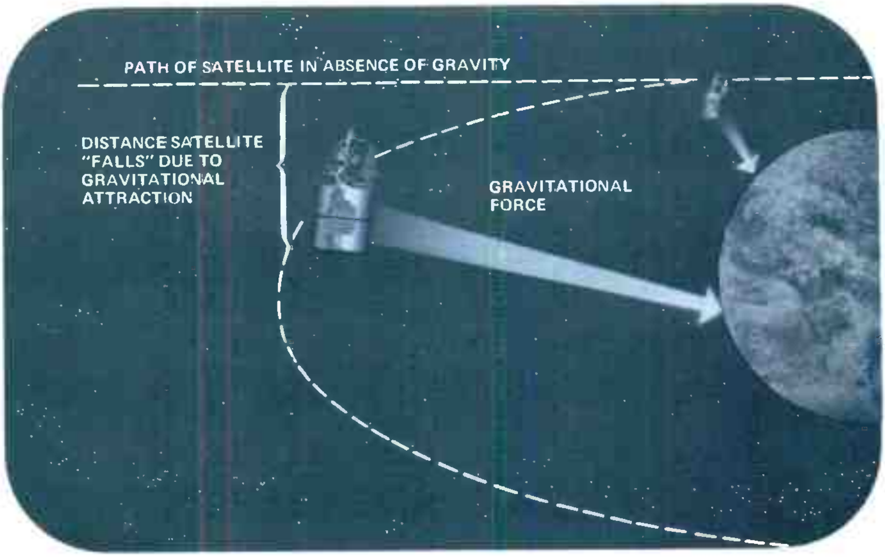

Figure 1. Tangential velocity of a satellite keeps it clear of earth, although it is constantly "falling" freely. When velocity, direction and gravitational field balance, satellite "falls" in a circular orbit. Because of small errors of speed or direction, most orbits are somewhat elliptical.

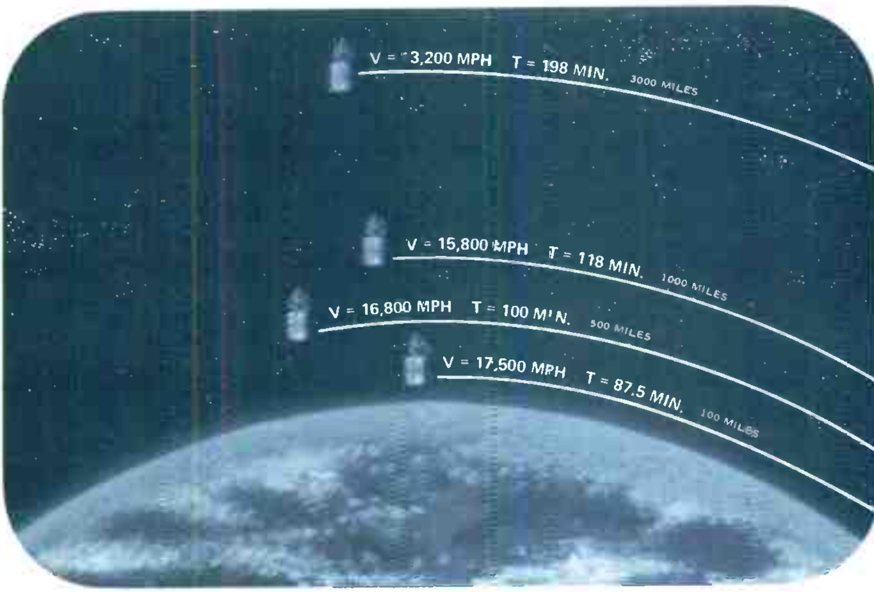

Figure 2. Gravitational force decreases with altitude, requiring lower velocities to maintain orbit. However, much more energy is required to drive the satellite to higher altitudes.

Virtually all commercial communications satellites are geosynchronous.

The advantages of a geostationary satellite can be emphasised by viewing it as a fixed microwave repeater, on a very high tower costing less than $2.00 per foot. The disadvantage is in the time delay which equals about 0.5 seconds round trip for a two way conversation. The delay also aggravates echo problems.

Placing a satellite in orbit requires a high ratio of rocket power to payload weight. This fact has substantially limited the size and weight of communications satellites. Since these satellites must carry their own primary power source into space, the weight and size limitations restrict the amount of energy available for electronics.

The primary power restriction limits the transmitter power output and number of channels that can be relayed. Nevertheless substantial technological improvements have been made in satellite communications since the first commercial communications satellite Intelsat I ("Early Bird") was launched in 1965. The satellite and other early efforts are described in the December 1966 issue of the Demodulator and summarized in the following paragraphs.

Historical Background

Long before communications relaying space vehicles became a reality, scientists eyed the natural satellite of the earth – the moon. Early in 1946 Project Diana bounced the first radar signals off the moon.

The first sounds to be transmitted, from outer spacd by a man-made device, were "beeps" from a transponder in the Russian Sputnik I, launched 4 October 1957. The United States entered the space age 31 January 1958 with Explorer I. Today commercial satellites stretch telephone circuits across the ocean, and telecasts from other continents are common.

American engineers placed the first communications satellite in orbit a year after Explorer I. Score – a short lived but highly successful "bird"-relayed messages up to 3000 miles and broadcast to the world a tape recorded Christmas greeting from President Eisenhower.

The 1960 flight of Echo I was witnessed around the world as the 100-foot balloon-like reflector satellite provided a "radio mirror" for powerful ground stations. Echo II went up in 1964 as experiments with passive reflectors continued.

An active repeater, Courier, extended the knowledge of space communications in 1960 with successful transmission of high-speed teletype, voice, and facsimile.

The commercial value of communications satellites was accentuated in 1962 with Telstar I, a joint project of NASA and AT&T. The first live telecasts between Europe and the United States added to the satellite's performance in transmitting high-quality voice, data, teleprint and other signals. Telstar II, and NASA's Relay I and II added more data to accent the value of satellite communications.

The Telstars were placed in lower, nonsynchronous orbits because it was believed the 0.5 second round-trip delay would be unacceptable. Subsequent experiments proved people can adjust to the delay very well.

By mid-1963, the first of three Syncom satellites was launched and communications milestones began to pile up. Syncom III brought the Tokyo Olympic games to the United States, and went on to demonstrate its value for all types of telecommunications. Subsequently, Syncom II and III were parked over the Pacific and Indian Oceans for use by the Defense Department. Although Syncom I achieved orbit, satisfactory communications were not established.

International Satellites

In 1962, before the first Syncom launch, Congress authorized the formation of a private company, Communications Satellite Corporation (Comsat). As authorized by its congressional charter, Comsat took the lead in forming the International Telecommunications Satellite Organization (Intelsat). Formed in August 1964, the original Intelsat organization included 11 member nations with Comsat representing the United States.

Any nation may joint Intelsat, providing they are willing to pay a proportionate cost of launching, operating and maintaining the satellite network. Each member nation is responsible for its own ground stations. Intelsat had 102 members by the end of 1978.

The previously mentioned Intelsat I, launched 6 April 1965 weighed 85 pounds. It was 28 inches in diameter and has a solar power capability of about 46 watts. The communications subsystem had two transpondors, one for each direction of traffic. The transmit power at the TWT output was 6 watts. The 25 MHz bandwidth afforded a capacity of 240 two-way voice channels or a single two-way television channel. The receive (up link transmit) frequency was in the 6 GHz band and the down link transmit frequency was 4 GHz. Intelsat I could only be accessed by two earth stations at one time.

The first Intelsat II satellite was launched 26 October 1966 but failed to achieve orbit. Three successful launches were accomplished in 1967. Those satellites had a bandwidth of 125 MHz and a power output of 18 watts. The increased power output allowed greater geographical coverage than was possible with Intelsat I. The increased bandwidth allowed multiple access for the first time. A number of ground stations could channel through the satellite simultaneously.

Quasi-linear transpondors were an essential part of the multiple access design. The transmitter output increased linearly with input power. When several signals were received simultaneously, the output power was divided among them in proportion to the received signal strength. This method reduced the possibility of intermodulation products and crosstalk.

Intelsat I was positioned over the Atlantic. One Intelsat II satellite was positioned over the Atlantic and two over the Pacific. They played an important role in providing communications for the Apollo space program.

The Intelsat III series of satellites provided significant increases in communications capabilities. Five successful launches were accomplished from 1968 to 1970. These satellites weigh 250 pounds, are 56 inches in diameter and have a solar power capacity of 160 watts.

The communications package consists of two transpondors, each with a bandwidth of 225 MHz. The increased bandwidth accomodates 1200 voice channels plus four television channels.

Some satellites are prevented from tumbling through space by giving them a spin of about 150 rpm about their longitudinal axis. This makes it impossible to use a conventional directional antenna.

Early communications satellites produced a toroidal shaped pattern which has about 9 dB gain over an omnidirectional antenna. Nevertheless, considerable energy was lost in the portion of the toroid not touching the earth. Intelsat III incorporates electronically despun antennas to provide a focussed beam instead of the toroidal pattern provided by earlier satellites (see figure 3).

Despun antennas increase the gain considerably. Minimum gain is 13 dB, with peak gain about 16 dB. The trick is to rotate the antenna in the opposite direction to the satellite, thereby keeping the "despun" beam pointed to earth.

Three types of despun antennas are possible: mechanical, electronically switched, and electronic. The mechanical method uses a directional antenna that is physically counter-rotated about the axis of the satellite. The greatest danger is mechanical failure. The electronically switched method systematically shifts rf power from antenna to antenna, keeping overlapping beams in the desired direction. The pure electronic approach selected for the Intelsat III satellites steers the beam by varying the phase of the signal as it feeds a series of radiating elements (see Figure 4).

The electronically despun antenna has three major subsystems: an earth center reference system, control circuits, and the radiating assembly. Two redundant horizon sensors scan the earth as the satellite rotates. Control circuits regulate the action of phase shifters, which direct the rf energy to the radiating elements of the antenna. The result is a radio beam continually focussed on the earth.

At synchronous altitudes, the earth's disk is just over 17° across. Allowing for satellite stabilization and

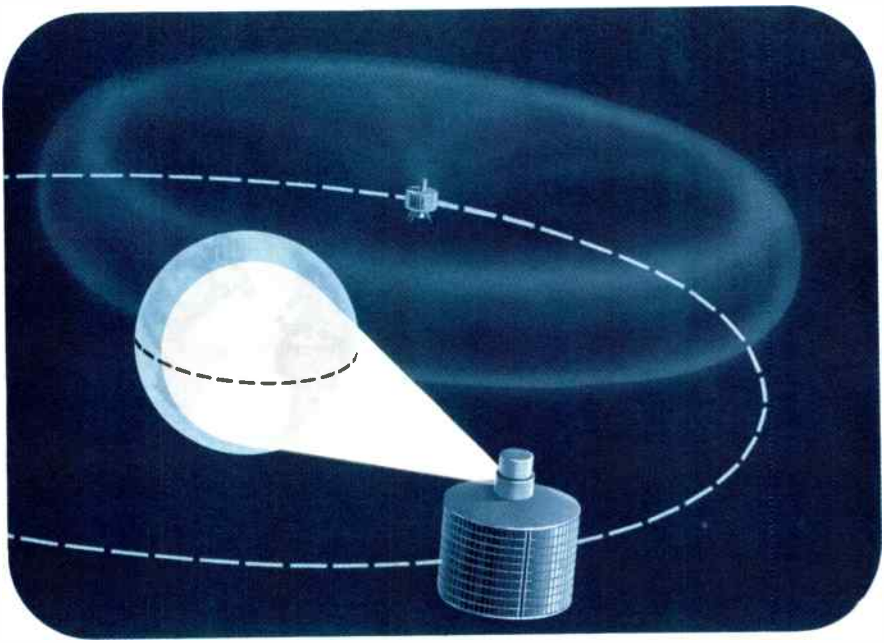

Figure 3. Toroidal pattern of first communications satellites (rear) loses much rf energy in space. Intelsat III focuses its communications beam towards earth, using despun antennas with up to 16 dB gain.

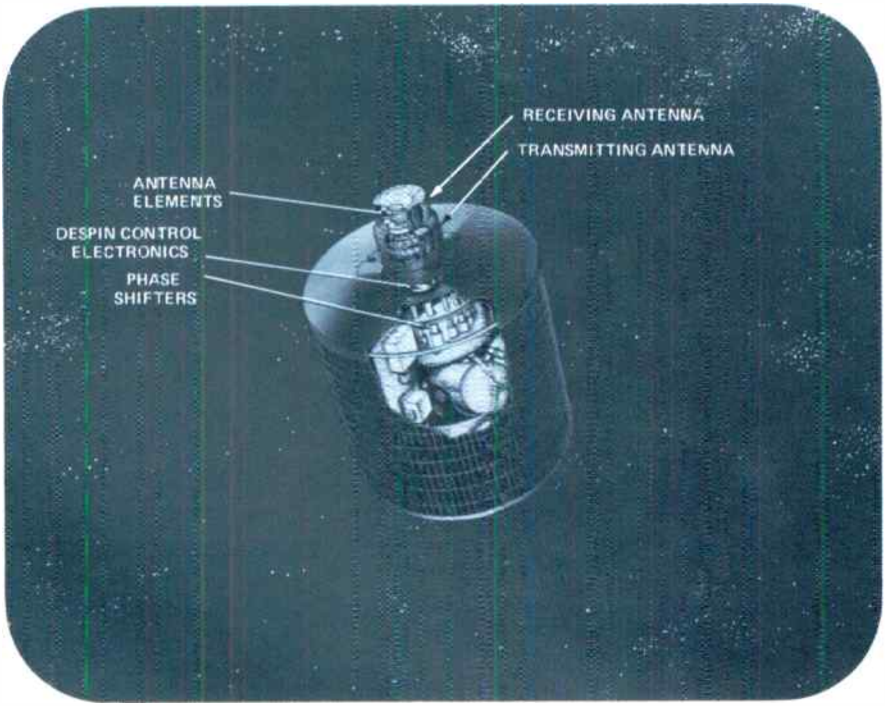

Figure 4. A cutaway drawing of the despun antenna system, initiated on Intelsat 3, shows placement of the phasers and radiating elements of the novel directional antenna developed by Sylvania Electronics Systems Division.

antenna tracking errors, a beam approximately 19° x 19° would adequately cover most points on the globe. For specific purposes, the beam can be made more directional, thereby increasing the gain. For example, a satellite designed to relay traffic only from the United States to Europe might have a fan-shapped beam 19° x 10° (long to the east-west). Minimum gain is increased to 16 dB with peak gain at 19 dB.

An alternative to spin stabilization requires no onboard thrusters or other control devices. Known as gravity-gradient stabilization, this method maintains the same side of the satellite always facing the earth. A long object in space tends to align itself vertically with the strongest source of gravity-in this case, the earth. Extendible arms make the satellite such a "long" object. Highly directional antennas can then be accurately pointed earthward. To date, all Intelsat satellites have used spin stabilization but some of the more modern domestic satellites use the gravity-gradient method.

The first of the latest Intelsat satellite series (series IV), was launched 26 January 1971. It uses 20 transpondors to provide 3,000 to 9,000 two way telephone channels or up to 12 TV channels. The tenth in the series was launched 26 May 1977. Not all of these "birds" are used for telecommunications. Some are for special broadcast and telemetry applications.

Six Intelesat IV satellites are in service providing an average of 6,250 two way telephone channels and 2 TV channels each, although various combinations are used by different satellites. Three Intelsat III satellites are still in service. Two are fully operational and the third is operating at 25% capacity.

Life expectancy of satellites is governed by the amount of fuel they can carry for on board positioning ("station keeping") thrusters. When the fuel is expended, the satellite begins to drift slowly westward. However, its communications capability may continue for some years.

Each successive generation of Intelsat satellites has shown a significant increase in design life expectancy over its predecessors. Intelsat I's design life expectancy was placed at 1.5 years. Intelsat II at 3 years and Intelsat IV at 7 years.

The increases partially resulted from improved engines and fuel. Ion pulsed and thermally augmented hydrazine thrusters may prove suitable for station keeping and consequently increase future satellites life.

The life expectancy of the electronics is primarily dependent on the source of electrical power. Photovoltaic (solar) cells are the primary source. These cells deteriorate with exposure to radiation, a common hazard in space.

Nevertheless, Solar cells will probably remain the principal source of primary power in space, although LES-8 and 9, launched by the U.S. 15 March 1976, use radioisotope, thermo-electric generators. These satellites are used for intersatellite communications.

In the future, more efficient solar cells with better response to the sun's total spectrum will provide greater output per unit area and the total area will be increased by deploying larger arrays. The satellites will be stabilized in three axes instead of spin stabilized. This will allow the entire solar array to be constantly oriented toward the sun.

Satellites in geosynchronous orbit are in constant sunlight, except for a few days each year, around the time of the summer and winter soltices. On those days, the satellites are in eclipse for a few minutes each day.

Satellites which are expected to function during these times must rely on storage batteries for power, so battery lifetime also affects satellite lifetime. Today's satellites use nickel cadmium batteries. Newly developed nickel hydrogen cells promise significant increases in battery life and consequent increases in satellite longevity.

Returning to the discussion of international satellites, Intelsat V to be launched in 1980, will provide 12,500 circuits plus two television channels. It will operate in the 12/14 GHz band in addition to the 4/6 GHz band.

Intelsat V will use global, zone and spot beam coverage and be able to switch transpondors between beams for maximum usage and flexibility. Simultaneous transmission and reception will be accomplished by orthogonally polarized antennas.

Today, all transoceanic "live" TV broadcasts and two-thirds of all transoceanic telephone and telegraph communications are via satellite. Predictions are that the demand for international satellite communications will increase 100% in the next 4 or 5 years.

Domestic Satellites

The Russian Molyina 1 satellite, launched 23 April 1965, was the first national or domestic communications satellite placed in orbit. This satellite had a 12 hour elliptical orbit. Its transmit output power was 40 watts. The Molyina satellites are able to relay voice, television and facsimile traffic. They also carry meteorological equipment and transmit "weather pictures" back to earth.

Canada was the first to place a domestic communications satellite system in geosynchronous orbit. ANIK 1 was launched 10 November 1972. It has a capability of 9,600 telephone circuits or 10 color television circuits. The latest in this series was launched 7 May 1975. It has the same communications capacity as its predecessors.

In December 1972, the Federal Communications Commission authorized domestic satellites for the United States. The first U.S. domestic satellite, Westar I was launched 13 April 1974. It has a capacity of 7,200 two-way telephone circuits or 12 color television channels. Figure 5 shows the domestic satellites currently serving the North American continent.

Indonesia was another early entrant in the domestic satellite field. Their Palapa I satellite was launched 8 July 1976. It is similar in design to the ANIK I and Westar birds. Palapa I has a capacity of 4,000 voice circuits or 12

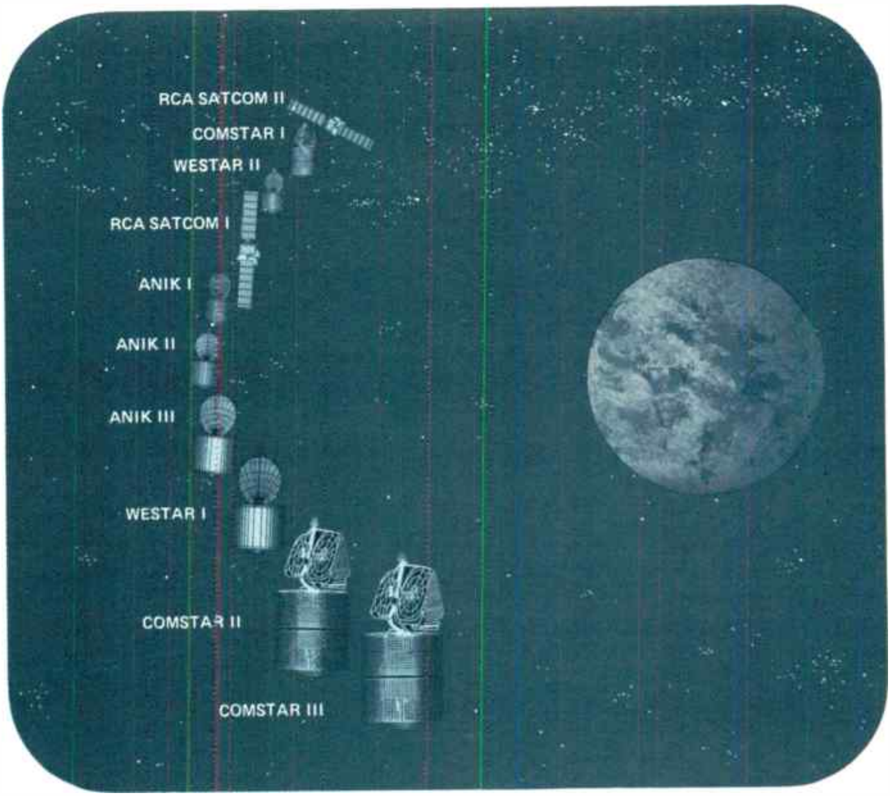

Figure 5. Domestic Satellites serving North America, – The three Comstar satellites are used jointly by AT&T and GTE to provide domestic telephone circuits.

simultaneous color television channels.

Nigeria has leased transpondors from Intelsat and set up earth stations for its own domestic system. Other nations, with operational systems using rented Intelsat capacity, include Algeria, Brazil, Norway, Saudi Arabia, Sudan and Zaire. The Phillipines have an operational system using rented capacity on Palapa I. India plans to launch its own, two-satellite, domestic system in 1981.

Regional System

What might be classified as a regional system, the United Kingdom's Skynet A, was launched 22 November 1969. The satellite was placed in orbit over the Indian Ocean and used for government communications. Skynet A was the first satellite launched by a Western European nation. The next two satellites in this series were unsuccessful. Skynet B launched 19 August 1970 failed to achieve orbit. Skynet II A launched 19 January 1974 orbited but could not establish communications due to a launch mishap. It decayed in January 1975. Skynet II B launched 22 November 1974 is successful.

France and West Germany cooperated to launch the Symphonie I, satellite 27 November 1974 and the Symphonie 2, 27 August 1975. These were the first European civilian communications satellites and among the first three axes stabilized satellites to be built. In contrast to spin stabilized satellites, three axes stabilized satellites do not rotate. The satellites use the 6 GHz up and 4 GHz down links. The transpondors have a 90 MHz bandwidth.

The Symphonie satellites were used in a series of tests for the United Nations. The tests involved the use of small, mobile antennas to quickly establish communications links in the event of a disaster. The German Red Cross maintains a vehicle suitable for this purpose and available for emergency use.

A European satellite system in the planning stage is Nordsat. This satellite will allow Denmark, Finland, Iceland, Norway and Sweden to share television and radio broadcast programs. Plans call for program broadcasting direct from the satellite to people's homes. This is in contrast to the method used in the United States where the CATV industry is a heavy user of satellites but uses an earth station receiver and another link between the satellite and the end user. The Demodulator will discuss the CATV industry in the near future.

Other regional satellite systems in the planning stage include Arabsat. This system will link the Arab Nations.

In May 1975, the European Space Agency was formed and brought together the entire range of European space capabilities. ESA's principal project, at present, is the development of the Ariane launch vehicle. This vehicle will serve the same purposes as the NASA space shuttle discussed later in this article.

The Future

The most critical limit on satellite communications is the radio frequency spectrum. This is a limited resource and its use is regulated by governmental as well as technical considerations. By 1990, the 4/6 GHz bands and probably the 12/14 GHz bands will be fully occupied. High density traffic will have to use the 18-30 GHz portion of the K band and even higher frequencies to meet worldwide demands beyond 1990. This will be true even though large scale memories, time division multiple access and even frequency sharing between satellites, using highly directive antennas, will be commonplace.

Another limited resource necessary to commercial satellite communications is the geosynchronous orbit. As stated earlier, this is a circular orbit about 22,270 miles above the equator. To an earth station, satellites in this orbit appear fixed in space. This greatly simplifies earth station design and circuitry by eliminating the need for elaborate tracking circuits and precision drive mechanisms for the antenna. However, there is a finite limit on the number of satellites that can be accommodated by the geosynchronous orbit.

A World Administrative Radio Conference (WARC) is scheduled for September 1979. Nearly every nation will be represented at this conference, which will be held in Geneva under the sponsorship of the United Nations International Telecommunications Union.

It is anticipated that the conference will reallocate significant portions of the frequency spectrum. It is also anticipated that WARC may attempt to allocate orbital slots for earth satellites. Many observers believe that the lesser developed nations will try to reserve orbital slots and portions of the frequency spectrum. Although these nations cannot presently use the frequencies and are many years away from launching a satellite, they believe that by the time they are ready, the more developed nations will have preempted the slots and frequencies. Under the one-nation one-vote rule, the emerging nations could pass measures favorable to their position, if they act in concert.

The decisions of the WARC will have an impact on future communications satellite developments. However, the frequency spectrum and synchronous orbit limits are technical problems and their ultimate solution lies in advancing the technology.

Strong incentives exist for developing the advanced technology. The expanding business communications market, which makes heavy use of domestic satellites, is expected to reach 2.5 billion dollars a year by 1985.

In the U.S. alone there were 4.7 billion interstate telephone calls made in 1977. A substantial number of these calls were relayed by Comstar satellites. Best estimates are that the number of annual interstate calls will increase to 9 billion by 1985. Satellite, terrestial microwave and long line capacities will have to be greatly increased to handle this traffic.

By the mid-1980's satellites with capacities of approximately 50,000 circuits will be placed in orbit. About that time, the size and weight problem will have been solved by launching from the Space Transportation System (Space Shuttle). Since most of the rocket power required by a satellite is used to escape the earth's atmosphere, a more favorable power to payload ratio will be obtained by launching from the shuttle. Furthermore, using the shuttle will reduce launch costs more than 50 percent.

Developed by NASA, the space shuttle is scheduled to go into orbit in late September 1979 for the first of six manned test flights. The first operational flights are scheduled for 1981, so the mid-1980's time frame for shuttle launched communications satellites seems reasonable. Figure 6 shows an artist's concept of the space shuttle.

These advanced satellites will deploy solar power arrays which will provide several kilowatts of primary power. The space shuttle itself will

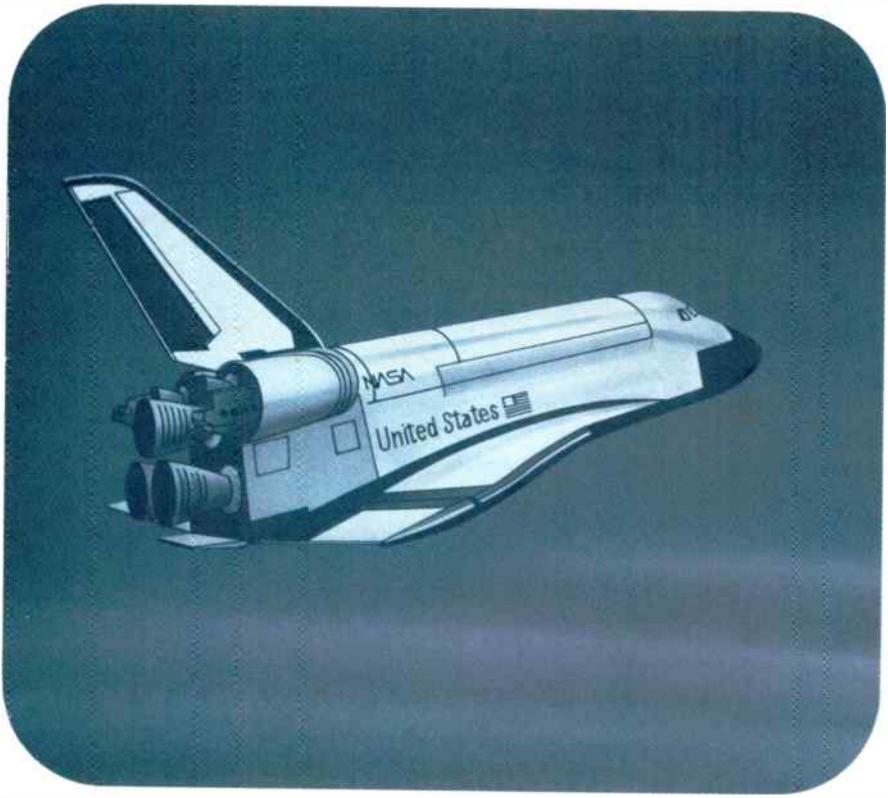

Figure 6. Space shuttle.

deploy a solar array to provide 12 kW of auxiliary power during an experimental flight in late 1980.

The shuttle launched satellites will be large and complex and use much larger, higher-gain antennas than the current models. They will probably operate in the 18-30 GHz portion of the K-band. They will employ fixed "spot-beams" directed to high-usage areas and beam or channel switching, in the satellite, for low usage areas. The increased satellite capability will make lower-cost earth stations feasible. Domestic satellite earth stations will be located on rooftops or in parking lots.

Sometime between 1985-1990 the communications satellites will become so large and complex, it will be more efficient to actually construct them in space. They will be built in a near earth orbit then propelled or towed up to geosynchronous orbit.

Space platform or station is a more descriptive name for these satellites. They will be as long as two or three football fields and mount 30 or more antennas. They will be able to handle a large variety of communications including voice, data, television, facsimile and electronic mail.

As satellites and their communications systems become larger and more complex, increased facilities will be required for monitoring, command, control and switching. On-board, microprocessor based, monitoring and control systems will automatically perform many of these functions. The system will check the performance of critical elements such as antennas arrays, power sources, transmission devices and switching circuits. The performance data will be stored and transmitted back to earth via telemetry. The data will be transmitted on a significant event, periodic or demand basis or some combination of all three.

The foregoing discussion of future satellites mentions a few highlights. The May issue will discuss these and other future developments in greater detail. Earth stations will also be described.

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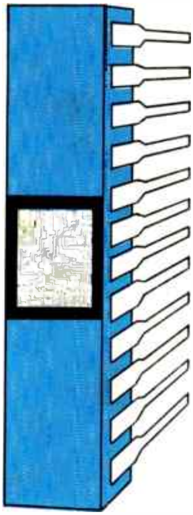


VLSI Codecs

Codecs on a single chip are one of large scale integration technology's latest contributions to telecommunications. In time, the telephone industry may use more codec IC's than it will microprocessors. This issue of the Demodulator describes some codec features, functions and circuits.

Codecs provide analog to digital conversion (coding) of transmit signals and digital to analog conversion (decoding) of receive signals. The conversions are referred to as A/D or D/A and codecs are occasionally called a/d/a converters. The word codec is derived from coder/decoder.

A/D/A conversions are a substantial part of the interface between analog voice circuits and digital transmission systems. A non-linear coding characteristic, either μ-law or A law is required for voice transmission. The LSI codec provides these functions on a single chip with consequent saving in cost and space. Furthermore, time division multiplexing and switching circuitry can be mounted on the same chip to provide additional saving and simplify installation, cabling and maintenance.

Today, codecs in the form of a small, dual, in-line package, are being installed in the individual channel units or line cards of some PCM systems. This is in contrast to older systems where the encoder (A/D converter) and decoder (D/A converter) are two PC boards in the common equipment shared by all channels.

In the new system, sampling, quantizing and encoding are accomplished in the codec. The digital outputs of the codecs are passed to a digital multiplexer and formed into a serial bit stream for transmission.

At the receive end, the signals pass through a digital demultiplexer to the individual channel codec for decoding.

Figure 1 illustrates the process. The advantages of single channel codecs are:

- Individual codecs are simpler and less expensive than high-performance, common-equipment units.
- Failure of an individual channel codec means the loss of a single

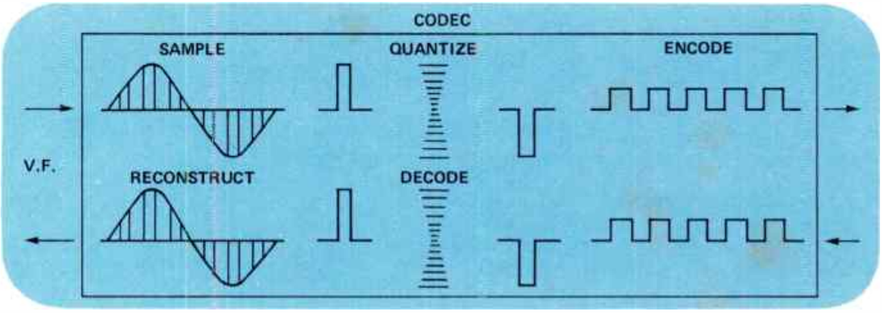


Figure 1. Codec functions.

channel. Failure of a common unit could cause the loss of an entire channel bank.

- Sampling the individual analog signals in separate units eliminates analog sampling crosstalk.
- Digital multiplexing is simpler and easier to accomplish than analog multiplexing.
- Companding to μ255 or A laws is accomplished on the chip.

Another advantage of some codecs is provided by a voltage reference built into the chip. These references are extremely stable. Their long term drift is negligible and they have quite low temperature and bias coefficients.

Therefore, when the telecommunications manufacturer incorporates these codecs in a channel unit, the transmit and receive levels can be precisely adjusted during factory tests. This eliminates the necessity for field adjustments when a channel unit is installed or replaced.

There are at least eight semiconductor manufacturers making per channel Codec chips. Most of these manufacturers offer more than one model. We have selected the Intel 2910 Codec as an example because it is similar to the codec used in the 9004A Channel Bank shown on the back cover.

The 2910 features μ255 law companding which is generally used in North America. Intel also manufactures another codec which companding according to the A law used in Europe. Other areas of the world may use either one.

Figure 2 is a photograph of an Intel chip. The overall area of the chip is about 22,000 square mils. Figure 3 is a block diagram of an Intel 2910 Codec. The critical conversion, comparison, voltage-referencing and buffering cir-

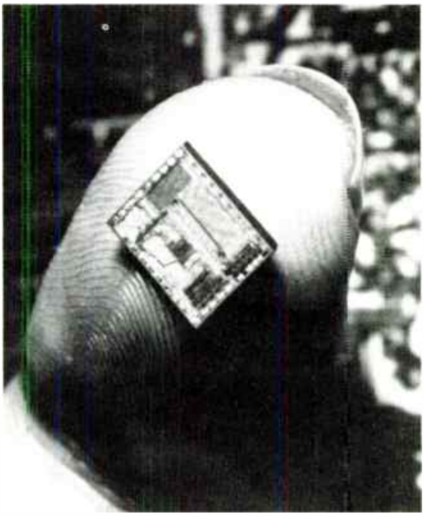


Figure 2. Photograph of an INTEL chip. Courtesy INTEL, INC.

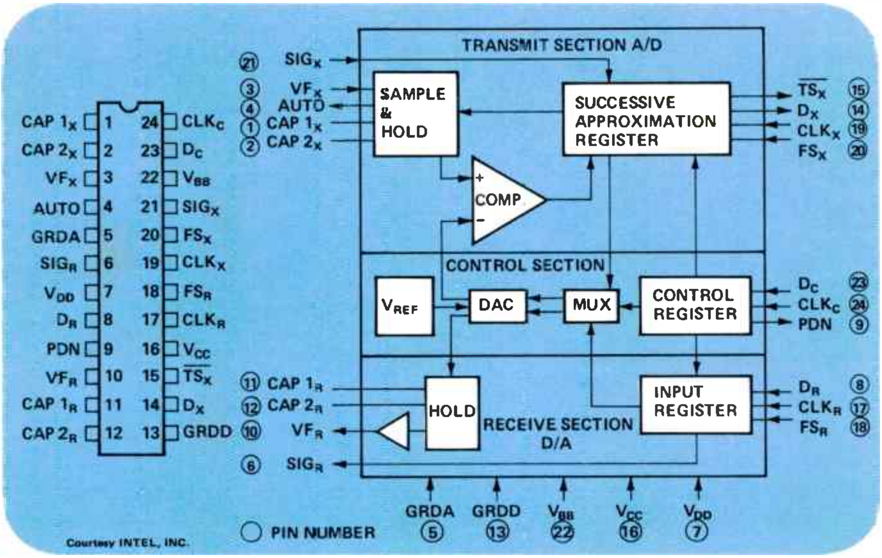


Figure 3. Pin configuration and block diagram for 2910 Codec.

cuits occupy less than 50% of the chip area, leaving the balance for logic interfacing.

Functional Description

The 2910 PCM Codec provides analog-to-digital and digital-to-analog conversions to interface a full duplex (4 wire) voice telephone circuit with the PCM highways of a time division multiplexed (TDM) system.

In a typical telephone system the Codec is used between the PCM highways and the line filters. It is interesting to note that these filters are also separately available on a LSI chip.

The Codec provides two major functions:

- Encoding and decoding of analog signals (voice and call progress tones).
- Encoding and decoding of the signaling and supervisory information.

On a non-signaling frame, the Codec encodes the incoming analog signal at the frame rate (FS_X) into an 8-bit PCM word which is sent out on the D_X lead at the proper time. Similarly, on a non-signaling frame of the receive link, the Codec fetches an 8-bit PCM word from the receive highway (D_r lead) and decodes an analog value which will remain constant on lead VF_r until the next receive frame. Transmit and receive frames are independent. They can be asynchronous (transmission) or synchronous (switching) with each other.

Every sixth frame is a signaling frame. On a signaling frame, the Codec transmit side will encode the incoming analog signal as previously described and substitute the signal present on lead SIG_X for the least significant bit of the encoded PCM word. Similarly, on a receive signaling frame, the Codec will decode the seven most significant bits and will output the least significant bit value on the SIG_r lead until the next signaling frame. The send and receive signaling frames, on the same chip, are independent of each other.

The call progress tones (dial tone, busy tone, ring-back tone, re-order tone), and the pre-recorded announcements, are sent through the voice-path. Signaling (off hook and disconnect supervision, rotary dial pulses, ring control) are sent through the signaling path.

Circuitry is provided within the Codec to internally define the transmit and receive time-slots, thereby minimizing the common equipment. This feature can be bypassed and discrete time-slots sent to each Codec within a system. In the power-down mode, most functions of the Codec are disabled to reduce power dissipation to a minimum.

Referring back to figure 3, the Codec is partitioned into three functional blocks. The top block is the transmit section or A/D converter (encoder). The bottom section is the receive section or D/A converter (decoder). The middle control section is common. The following paragraphs discuss each section in turn.

Transmit Encoding

The vf signal to be encoded is connected to the Codec's sample and hold circuit through Vfx. Sampling is accomplished by an internal switch. The hold function is performed by an external capacitor connected between Cap 1x and Cap 2x. A 2000 pF, 20% capacitor is suitable for an 8kHz sampling system.

The sampling and conversion is synchronized with the transmit time-slot (worst case conversion time, 20 slots). The PCM word is outputted to Dx when the proper time-slot occurs in the following frame. The process is presented graphically in figure 4.

Receive Decoding

The PCM word from the PCM highway enters the Codec at D_r when the proper time-slot occurs. The decoded value is held on an external capacitor connected between $Cap1_r$ and $Cap2_r$. A 560 pF, 20% capacitor is suitable for 24 time-slots and an 8kHz sample rate. The buffered output at Vf_r is equal to the stored voltage on the capacitor and remains constant until the next receive frame.

Signaling

The duration of the frame synchronization pulses determines whether a frame is a non-signaling frame or a signaling frame. A frame sync pulse

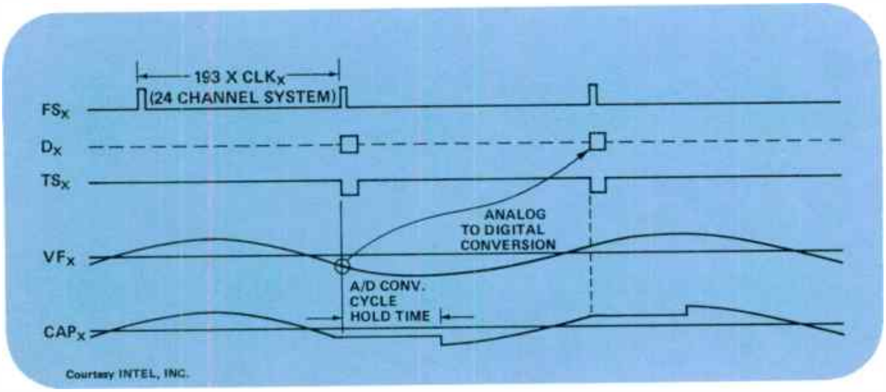


Figure 4. Analog to digital conversion.

which is one clock period in duration is a non-signaling frame. A frame sync pulse which is two clock periods in duration is a signaling frame.

On the transmit side, when the FS_X pulse is widened, the 8th bit of the PCM word is replaced by the value on the SIG_X input. On the receive side, when the FS_r pulse is widened the 8th bit of the PCM word is detected and placed on the SIG_r lead. That output is latched until the next receive signaling frame.

The remaining seven bits are decoded according to the values given in CCITT recommendation G733. The SIG_r lead is reset to a TTL low whenever the Codec is in the power down state.

Control Section

The operation of the 2910 is defined by serially loading an 8-bit control word through the Dc (data) lead and the CLK_C (clock) lead. The loading is asynchronous with the other operations of the Codec, and takes place whenever transitions occur on the CLK_C lead. The D_C input is loaded in during the trailing edge of the CLK_C input. This operation is shown in Figure 5.

The control word contains two fields:

Bit 1 and Bit 2 define whether the subsequent 6 bits apply to both the transmit and receive side (00), the transmit side only (01), the receive side only (10) or whether the Codec should go into the standby, power-down mode (11). In the latter case (11), the following 6 bits are irrelevant.

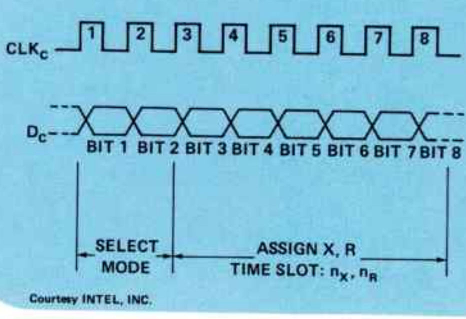
The last six bits of the control word define the time-slot assignment, from 000000 (time-slot 1) to 111111 (time-slot 64). Bit 3 is the most significant bit and bit 8 the least significant bit and last into the Codec.

The Codec will retain the control word (or words) until a new word is loaded in or until power is lost. This feature permits dynamic allocation of time-slots for switching applications.

The foregoing discussion described what the Codec does. The following paragraphs describe how it does it after briefly reviewing the μ255 law to explain why certain specifications are imposed on Codec design.

μ 255 Law

Message signals have a dynamic range of about 40 dB, and subjective



BIT 1	BIT 2	MODE
0	0	X & R
0	1	X
1	0	R
1	1	STAND-BY

BIT 3 8	TIME SLOT
0 0 0 0 0 0	1
0 0 0 0 0 1	2
.	.
.	.
.	.
1 1 1 1 1 1	64

Figure 5. Control word.

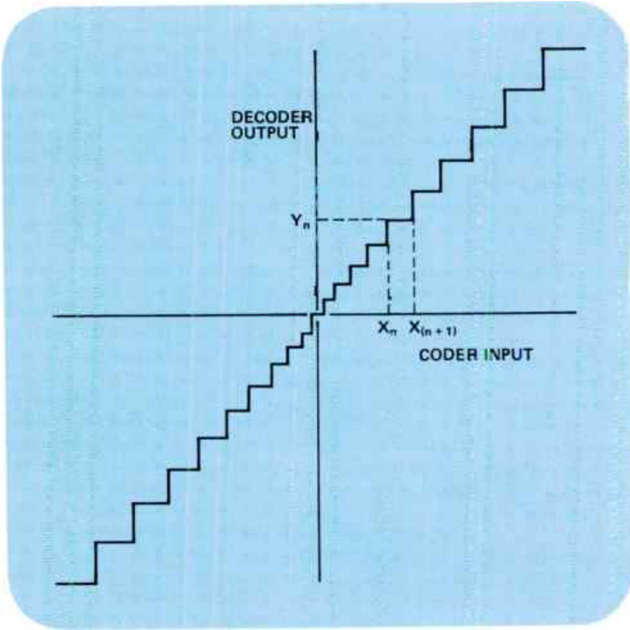


Figure 6. Non-uniform Codec transfer characteristic – more steps per volt for small samples than for large samples maintains a substantially constant S/D ratio.

listener tests show a preference for a constant signal-to-noise ratio over that range. Therefore, a coder characteristic is needed which produces a relatively constant signal-to-quantizing-distortion ratio (S/D) over a wide range. To achieve this, a modified natural logarithmic compression law is used in which the output coder signal (Y) is related to the input signal (X) by the expression:

$$Y_n \text{ (Sign X)} = \frac{l_n(1+\mu|X|)}{l_n(1+\mu)}$$

This is referred to as the μ-law.

Since the compression law is a logarithmic law, the coder decoder (Codec) combination which produces it must be non-linear or non-uniform. In previous systems of the D1 type, this was done by means of a diode-type compressor (which produced the logarithmic compression law) followed by a linear-coder. A linear decoder and diode-type expandor completed the translation back to the original signal.

However, more efficient coding means have been developed, and the coder and decoder are designed as a non-linear Codec without the intermediate diode compression. In the coder, samples of the voice signal are compared against a set of discrete steps, and the step nearest the sample is represented by a digital code. The decoder then produces an output dictated by the code.

The logarithmic compression law gives more steps per volt for small speech samples than for large samples, thus maintaining a constant signal-to-quantizing-distortion ratio (see figure 6). Referring to the figure, if X represents the coder input and Y the decoder output, then for small values of X the steps are fine, while for larger values of X the steps are more coarse. The coder has only a discrete set of steps with which to represent a signal.

Note that if the coder input is a sample of height anywhere between X_n and X (N+1) the decoder output Y_n will be produced.

Compressed Coding

The choice of a compression law with $\mu = 255$ is the consequence of the use of an EDL code (Efficiently Digitally Linearizable logarithmic companding coding law). Using this law produces an 8-bit code which has unequal coding steps, as shown in Figure 6, but which may be readily converted to a 13-bit linear code which represents the sample height if all coding steps were equal. This conversion from a compressed code to a linear code can be done by digital means using binary logic – hence "Efficiently Digitally Linearizable."

To achieve a digitally linearizable compression law, the characteristic is approximated by a number of Straight line segments, as shown in Figure 7. The characteristic is made up of eight segments positive (0-7), and eight segments negative (0-7). However, the two segments nearest zero are collinear. Therefore, they are considered as one, so the curve is approximated by 15 segments.

Each segment of Figure 7 is composed of a number of coding steps which meet following requirements:

– (1) Each segment has the same number of coding steps.

– (2) The coding steps within each segment are equal.

– (3) The steps on all segments are integral multiples of the smallest step.

Furthermore the step sizes on adjacent segments are related by powers of two, so they can be implemented by binary methods. Therefore, the compression law is efficiently digitally linearizable.

If a μ law curve is fitted to a segmented compression curve con-

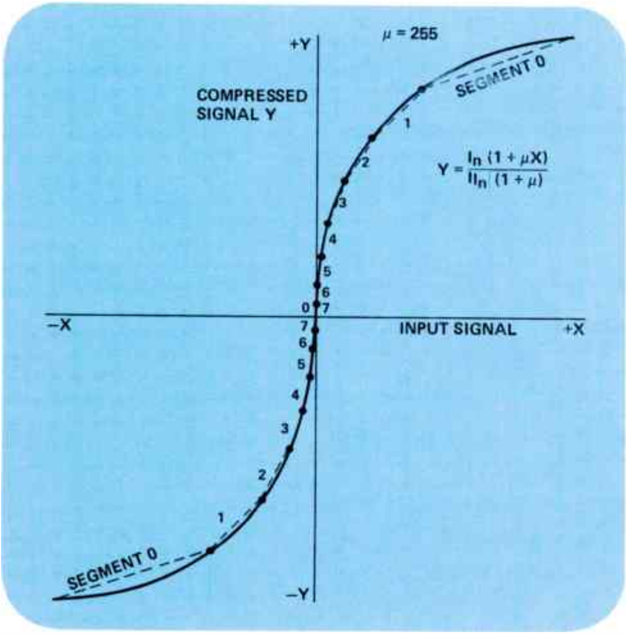


Figure 7. Segmented compression characteristic – mathematicians refer to the segments as "chords."

structed with 15 segments and 16 equal steps per segment, with step sizes in a ratio of 2:1 on adjacent segments and all step sizes an integral multiple of the smallest step, then the closest fit will cause μ to equal 255.

Codec Circuit Descriptions

In a PCM system, a time varying voltage is sampled and the sample is compared to a set of discrete steps. The step closest to the sample is represented by a digital code which can be transmitted.

In our Codec example, the sampling is accomplished in the sample and hold circuit; the discrete steps are generated in the control section DAC and the comparison between the sample and the steps is made by the A/D comparator.

Comparator Circuit

Since the μ255 first A/D conversion level is below 400 μV, the comparator requirements are quite stringent particularly with reference to the offset voltage. A chopping technique for offset nulling is used to meet this requirement.

The technique uses holding capacitors to store the amplifier offset and chopper switches to charge the capacitors. Figure 8 is a block schematic of the comparator.

Referring to the figure, the chopper switches periodically ground both the inputs and outputs downstream from the coupling capacitors so they charge to the offset voltage of the amplifier. Since the amplifier has differential outputs, one half the offset is stored on each capacitor. When the chopper connects the inputs and outputs back to the normal signal path, the offset voltage is effectively subtracted from the signal.

The high resolution and large dynamic range required for μ law companding also make high gain a necessary comparator characteristic. The 2910 cascades comparator stages to bring the signal to a level which can be resolved by a conventional sense amplifier.

The cycle time of the comparator is the time required to sample and capture the offset voltage, propagate the input signals through all stages of the comparator and to sense and latch the result. The 2910 comparator's cycle time is 2.5 microseconds.

DAC Circuit

The companding law requires a digital to analog converter with a

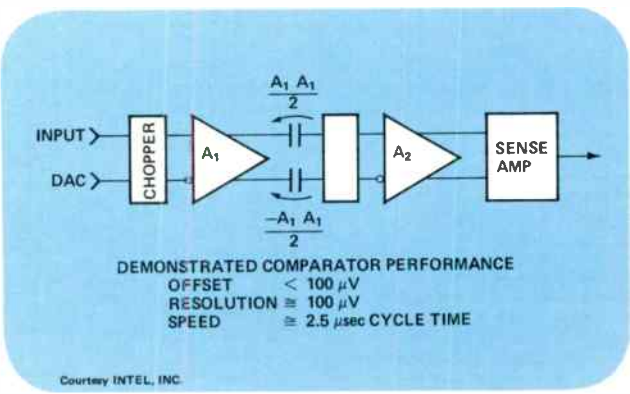


Figure 8. Low offset, high gain NMOS voltage comparator.

logarithmic transfer characteristic. The 2910 DAC provides this characteristic by a voltage divider composed of a series of weighted, diffused resistors. Each weighting resistor is shunted by a second voltage divider consisting of a loop of unit resistors.

The loop unit resistors provide a linear division of the voltages at the loop end points. Each unit resistor has an associated transmission gate to provide access to its nodal voltage. A total of 256 resistors and 256 transmission gates are used. Appropriate decoding is provided so that only one gate can be accessed at a time.

As previously stated, the DAC provides one input to the comparator. The comparator provides an input to the successive approximation register. The final output is an eight bit code which represents the closest approximation to the sample.

The first bit in the code is a sign bit, a 1 for a positive or a 0 for a negative sample. The next three bits can form eight binary combinations — they identify which of the eight positive or eight negative segments of the μ 255 compression curve was used in the coding. The last four bits indicate which of the 16 coding steps, in the unit resistors loop of the segment, was used to form the final height of the sample.

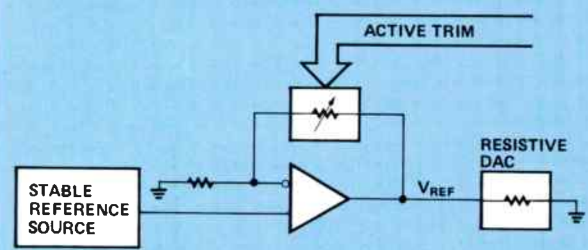
As shown in Figure 3, the DAC is used by both the transmit and receive channels. An internal interrupt prevents both channels accessing the DAC at the same time. The encoding operation may be interrupted to do a decode. The decoded value is stored in the capacitor and outputted. Then the encode operation is resumed.

Voltage Reference

The voltage reference is the current source for the DAC. The voltage level and stability of the voltage reference are critical because they directly effect the long term gain stability of any voice channel where the Codec is used. Gain variations can cause voice circuits to oscillate or sing.

The 2910 uses two devices with different thresholds to generate a refer-

Figure 9. Actively trimmed NMOS voltage reference using threshold subtraction technique.



CODEC LIFETEST DATA	
V_{REF} DRIFT, VOLTS/YR	GAIN VARIATION AT 40 YEARS
10^{-4}	0.012 dB @ 85°C

Courtesy INTEL, INC.

ence voltage equal to the difference. Flat band differencing is used to perform first order nulling of the temperature and voltage coefficients.

The reference potential is buffered by a programmable gain amplifier. The gain of the amplifier is trimmed during initial wafer testing to provide a buffered reference voltage of 3.15 volts. This is a neat bit of engineering economy since the buffer amplifier is needed anyway to provide current drive for the DAC. The voltage reference circuit is shown in Figure 9.

This issue of the Demodulator has described the Codec as a device and briefly mentioned how it fits into overall systems. A future issue will discuss how Codecs and other very large scale integrated devices are being used in the latest telecommunications systems.

The eventual placement of a Codec on every subscriber's premises may be the final step in the formation of an all digital network. This seems to be the direction in which the industry is heading.

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