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HIGH DATA RATE SYSTEMS FOR THE FUTURE

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BACKGROUND

We are truly living in the information age. Information systems in the next century will transfer data at rates that are much greater than those in use today. The reason for increasing data rates is simple. All of us will be using sophisticated communication devices that require large amounts of data sent to and from them, in as small of an amount of time as possible, in order to maintain the user friendliness of these systems.

Some of these systems of the future include high resolution multi-channel television, high speed facsimile, high speed videotext, and large volume data dissemination services. Business will use such media for electronic mail, on-line libraries, financial reports, and computer forums. The home user will benefit from these services for entertainment, interactive shopping, and library services that include electronic newspapers, publications, periodicals, and encyclopedias.

The users of these systems will be located in high density urban areas, rural areas, and in some cases very isolated, remote areas. Independent of where the user is located, it will be necessary to network users in these different areas. Satellite based communication systems will play an important role in networking these users, whether it be from a user in one urban area to a user in another urban area, or whether it is from a user in a more populated area to a user in a very isolated, remote area.

A typical satellite based communication system is shown in Figure 1. While data rates between a satellite and ground station can be expected to be very large, the data rates between satellites can be expected to be even larger. In addition to this scenario that will provide transmission of data used for commercial communications purposes, NASA has its own high speed data communications requirements. Figure 2 represents the use of tracking and data acquisition satellites to deliver science and engineering data from various scientific spacecraft to ground stations. These tracking and data acquisition spacecraft will be connected together by "crosslinks" to enable the system to maintain near continuous communication with low earth orbiting scientific spacecraft. Again, the data rates that are transmitted between the tracking and data acquisition spacecraft may be quite large.

SOME TYPICAL DATA RATES

For NASA's data transmission requirements, studies have been conducted on spacecraft that will be launched in the year 2000 and beyond. The spacecraft that have high data rate requirements all have earth imaging instruments on board. The raw data rates that these instruments are expected to output range from about 700 megabits per second (Mbps) to 1300 Mbps. Other studies have been conducted to estimate the data rates that will be required for the tracking and data acquisition satellite to tracking and data acquisition satellite "crosslink". Most of these studies indicate that data rates of 2 gigabits per second (Gbps) will suffice for crosslink applications through the year 2010.

Similar studies have been conducted for commercial communications applications. Some of these project that data rates of 600 or 700 Mbps will suffice for the intersatellite communications link, while others project that a rate of 2 Gbps is more realistic. When one considers that a single high definition digital television signal can require transmission at 650 Mbps or higher, the 2 Gbps estimates could be extremely conservative.

MICROWAVE, MILLIMETER WAVE, OR OPTICAL

Microwave frequencies, that is those below 30 gigahertz (GHz), can be considered for high data rate transmissions. As the microwave band that could support the highest data rate is only about one GHz wide, this would translate into its only being able to handle data at rates up to one gigabit per second using conventional (quatenary phase shift keying) techniques. Another serious drawback is that these frequencies are allocated for services other than space communications. Radiolocation and radionavagation services represent potential sources of interference for systems using these frequencies.

Millimeter wave frequencies, those above 30 GHz, are suitable for high data rate communication systems. There are frequency bands that have been allocated exclusively for earth-to-space, space-to-earth, and space-to-space applications. There is an additional advantage to using some of the frequencies within the millimeter wave region. Figure 3 illustrates the typical attenuation through the earth's atmosphere for frequencies from 30 to 250 GHz. Some frequencies, such as those around 60, 120, and 180 GHz exhibit an extremely large amount of attenuation through the earth's atmosphere due to oxygen and water vapor absorption. By using frequencies that have been allocated around these absorption bands, space-to-space communication systems may be designed which will have a near zero probability of being interfered with from sources on the earth.

Optical communications technology is also very attractive for high data rate communication systems. Extremely large amounts of bandwidth are available to serve practically any application. Earth-to-space and space-to-earth optical communication systems present great challenges to optical communications technology. The presence of clouds or fog, and other atmospheric phenomena, make communications through the atmosphere almost impossible except under the best of conditions.

There have been numerous studies conducted that have compared millimeter wave with optical communication systems. The results of these studies have often been biased depending upon the organization that has funded the study.

In general, these studies have indicated that millimeter wave systems have advantages over optical systems in that millimeter wave technology is more mature, and that pointing and tracking requirements for millimeter wave systems are not as critical as for their optical counterparts. Optical systems are more attractive from the aspect that they require smaller apertures than millimeter wave systems for the same data rate. The diameter of the telescope for an optical communications system is often an order of magnitude less than the diameter of the antenna that is needed for a comparable millimeter wave system.

These studies have usually indicated that the preferred system is a function of data rate, with millimeter wave systems being the choice for lower data rates, and optical systems being the choice for higher data rates. The "crossover" frequency at which both types of systems are equally attractive has been found to be anywhere between 50 Mbps and 2 Gbps.

As it is currently believed that both millimeter wave and optical systems will share the burden of high data rate transfer in the future, the Goddard Space Flight Center has been active in developing technology for both systems. Many of the components, such as multiplexers, demultiplexers, AGC amplifiers, and real time error performance measurement systems are applicable to both millimeter wave and optical systems.

TECHNOLOGY TO IMPROVE MILLIMETER WAVE COMMUNICATIONS

A typical millimeter wave communication system is illustrated in Figure 3. The high rate data modulates the millimeter wave carrier, and is then amplified before being delivered to the (transmitting) antenna system. The receiving terminal would most likely employ a low noise amplifier to improve receiver sensitivity, down convert the millimeter wave signal to an intermediate frequency (IF), and then demodulate it.

Goddard Space Flight Center's Microwave Technology Branch has been active in developing millimeter wave technology for several years. The frequency band of 59 to 64 GHz has been selected for intensive development in that it makes 5 GHz of bandwidth available, and that this band has been allocated exclusively for space-to-space communications. The 59 to 64 GHz band is also lower in frequency than some of the other millimeter wave intersatellite bands, which makes component development somewhat easier.

Modulator/Exciters

The modulator/exciter generates the millimeter wave (60 GHz) signal to be transmitted, and superimposes the high data rate digital signal upon it. The modulation technique that has been selected for the development effort is quaternary phase shift keying (QPSK). QPSK was selected as it represents a compromise between efficiency (the number of bits per second that can be transmitted per unit bandwidth), and the technical complexity of the hardware. It is also used by NASA in many space communication applications.

As it was previously very difficult to directly modulate a 60 GHz carrier, initial efforts consisted of generating a high quality 15 GHz signal, modulating it, and then frequency multiplying the modulated signal by 4. This was a satisfactory approach, however, a large amount of power at 15 GHz was required due to the poor efficiency of the times 4 multiplier. This technique had one other disadvantage. The effects of any non-linearities in the modulation process at 15 GHz were multiplied by four in the frequency modulator.

With the advent of high performance, high speed schottky switching diodes, an effort was initiated to develop a modulator/exciter that would directly modulate a 60 GHz carrier. A Gunn oscillator, integrated on a quartz substrate with a coupler and a harmonic mixer, was phase locked to a 15 GHz source, which was then phase locked to a 2.14 GHz high stability source. The modulator was constructed using microwave integrated circuit techniques on a sapphire substrate. The resulting component was a modulator/exciter, with less than two degrees of non-linearity, capable of handling 2 Gbps of data on each channel, for a total of 4 Gbps.

Solid State Power Amplifiers

Early Goddard efforts concentrated on the silicon IMPATT (Impact Ionization Transit Time) device, and circuits that would combine the output power from multiple IMPATTs to realize higher output power. The silicon IMPATT was chosen as there was extensive reliability data on these devices, and mean device lifetime was a direct function of the operating temperature of the device.

A breadboard amplifier was developed that combined four IMPATTs in the output stage, and delivered 4 watts across a 2.5 GHz band centered at 60 GHz, with an input power of 4 milliwatts. This represented the first time ever that high power double drift IMPATT diodes were successfully used in a broadband stable amplifier. A second effort was undertaken to combine 16 "off-the-shelf" IMPATTs using a novel radial line combining technique, to deliver 10 watts of power. Although 60 GHz combining efficiencies of over 90% were demonstrated, the completed amplifier exhibited a DC to RF efficiency of slightly less than 6 percent.

An effort is underway to develop a solid state amplifier with at least 10% DC to RF efficiency at the 10 watt level. To accomplish this, the output from eight Gallium Arsenide IMPATTs are being combined in a special low loss waveguide combining structure. Since the initial silicon IMPATT activities, much has been learned regarding the reliability associated with high power Gallium Arsenide devices, and Gallium Arsenide IMPATTs now deliver more power per device, at higher DC to RF efficiencies, than their silicon counterparts.

Beam Waveguide Transmission Systems

Connecting a transmitter/receiver to a millimeter wave antenna system is a formidable problem. Coaxial cable, useful at RF and lower microwave frequencies, cannot be considered for millimeter waves, due to the high loss. Waveguide, which is much less lossy than coax, is also impractical for long transmission lines. The standard waveguide which is used at 60 GHz has a loss of 0.07 dB per inch. This means that half of the received or transmitted signal will be lost for every 3.6 feet that the signal travels through such a waveguide.

To permit the transmitter/receiver to be located up to several meters from the antenna feed, beam waveguide technology is being investigated as an alternative to conventional waveguide and rotary joints. Although final measurements have not been made, an engineering model beam waveguide transmission system for 60 GHz has been fabricated which consists of mirrors, a motorized system that can slew on two axes, and a six port network for interfacing with the antenna horn.

Low Noise Receiver Technology

Before the advent of low noise amplifiers that operate at 60 GHz, it was envisioned that a low noise mixer front end receiver would interface directly with the antenna system. To realize small size, light weight, high performance receiving subsystems, an integrated receiver approach was taken. A low noise crossbar stripline balanced mixer was integrated with a phase locked Gunn local oscillator and a harmonic mixer on a single quartz substrate. A wideband low noise IF amplifier was fabricated on a separate substrate, and the necessary phase lock electronics and frequency source was fabricated in a separate miniature package. This technology still represents the basic configuration that will be used to down convert a 60 GHz signal to a lower IF for demodulation.

One of the first technologies investigated to improve the sensitivity of the mixer front end receiver was the

Superconductor-Insulator-Superconductor (SIS). This device, when used as a mixer, offers potential conversion gain, requires extremely low amounts of local oscillator power, and offers potential sensitivities near the fundamental quantum limit. Unfortunately, the device only operates at extremely low physical temperatures. The unavailability of long lifetime closed cycle refrigerators for spacecraft use, plus the availability of a new semiconductor device, the High Electron Mobility Transistor, has shifted attention away from the SIS for spacecraft applications, at least for the future.

Three terminal devices were also investigated as a means of improving receiver sensitivity. An effort was undertaken to improve conventional GaAs MESFETs (Gallium Arsenide Metal Semiconductor Field Effect Transistor) by shortening the gate length, decreasing the gate resistance, and decreasing the gate capacitance. While good results were obtained at 60 GHz, a new device became available which exhibited even better performance in terms of sensitivity. This device, the High Electron Mobility Transistor (HEMT), has become the best device for achieving low noise gain at frequencies up through about 90 GHz. Considerable effort was spent in developing state-of-the-art devices and circuits. Single, two, and three stage amplifiers were fabricated and tested. The resulting amplifiers are capable of improving the sensitivity of the previously developed mixer front end receiver by a factor of about five.

TECHNOLOGY TO IMPROVE OPTICAL AND MILLIMETER WAVE COMMUNICATIONS

Goddard's Microwave Technology Branch has also been developing high speed electronics that are applicable to both optical and microwave/millimeter wave communication systems. These electronics are used for multiplexing data from several sources, encoding the data for transmission, adjusting the received signal levels, recovering the data and clock signals, and providing a means of measuring the performance of the system in real time.

Figure 5 represents the electronics that are associated with either an optical or a microwave/millimeter wave system. The multiplexer combines digital data from several sources. The multiplexed signal is then encoded. Optical systems are being designed which use a pulse position modulation format. This is critical to optical systems to limit the average power from the laser transmitter, while keeping the ratio of peak to average power as high as possible. An automatic gain control (AGC) amplifier is used to adjust the received signal to deliver a constant output to the bit synchronizer. Such adjustments are necessary due to fluctuations in input signal from the pointing, acquisition, and tracking system associated with the optical telescope, or the millimeter wave antenna. The bit synchronizer recovers the transmitted data and clock. The data can then be demultiplexed to reconstruct the original sources. A pseudo random code generator and bit error detector provides a means of measuring the real time performance of the system.

Communication electronics components that perform all of the above functions have been designed for an optical system that operates at 50 Mbps and an optical system that operates at 650 Mbps. Components have been fabricated and tested for a breadboard system that operates at 50 Mbps. These components include a binary pulse position modulation encoder, an AGC amplifier, data detection filters, and a bit synchronizer. Development in this area has used conventional emitter coupled logic and complementary metal oxide silicon (CMOS) logic devices for the components that operate at 50 Mbps. To operate at 650 Mbps, high speed Gallium Arsenide devices are used with fabrication implemented on multilayer printed circuit boards.

POTENTIAL COMMERCIAL APPLICATIONS

All of the technology previously described has commercial applications. While the components developed for space-to-space communications at 60 GHz may not have specific commercial applications, it is very possible to modify them slightly for operation at different millimeter wave frequencies. This would enable them to be used for extremely wide band, high data rate transmissions over short to moderate (line of sight) distances. The local networking of several high speed computer centers is one possible application.

To serve the remote user in an isolated area where conventional hard wired or fiber optic facilities would be prohibited, microwave and millimeter wave systems would enable the user to receive large quantities of high rate data in short periods of time. Such a system could also be interactive, or bi-directional, allowing the remote user to transmit either low data rate requests or large volumes of data at high speed to another location.

The high speed communication electronics work is also directly applicable to commercial users. Much of this technology is just as applicable to fiber optic transmission as it is for transmission through the atmosphere. High data rate terminals could be developed that would allow local transmission of high data rates between multiple nodes. Such systems could be built with adequate margin to operate over short distances in the presence of moderate precipitation. If these margins are not incorporated into the system, use of the system could be restricted to periods when precipitation or fog are not intense enough to preclude accurate transmission of data.

The use of high data rate communication systems will become increasingly important in the future. Sophisticated communication devices of the future will require it. Increasing costs of transportation will make it economically desirable. Uses of these systems will only be limited by the imagination of the system designers of the future.

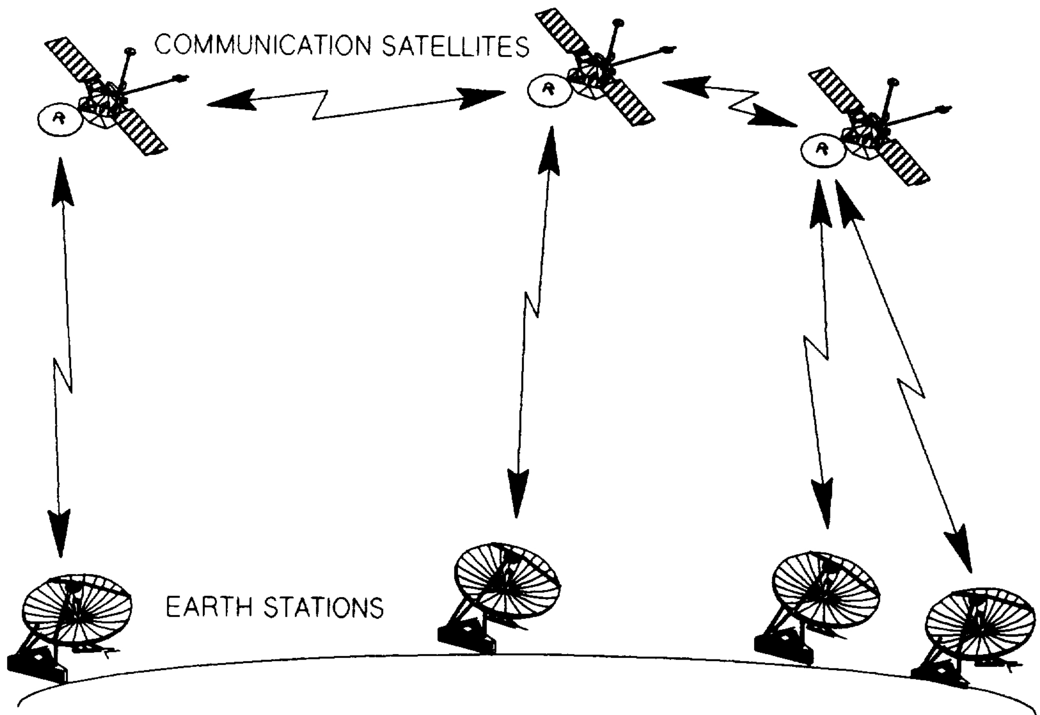

FIGURE 1. COMMERCIAL SATELLITE BASED SYSTEM

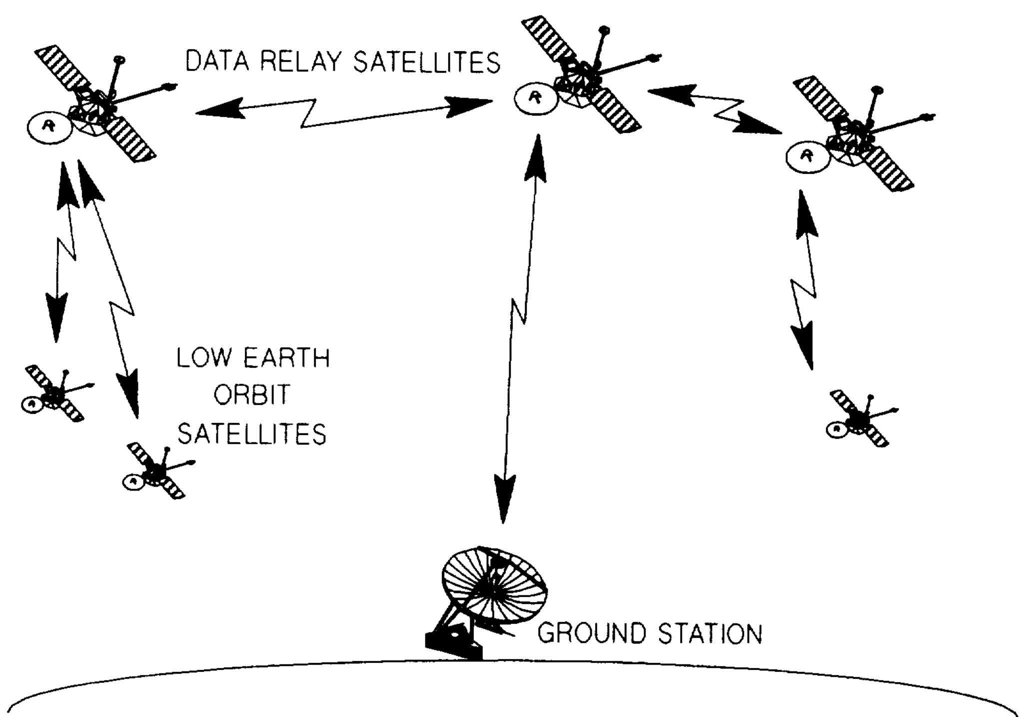

FIGURE 2. NASA SATELLITE BASED SYSTEM

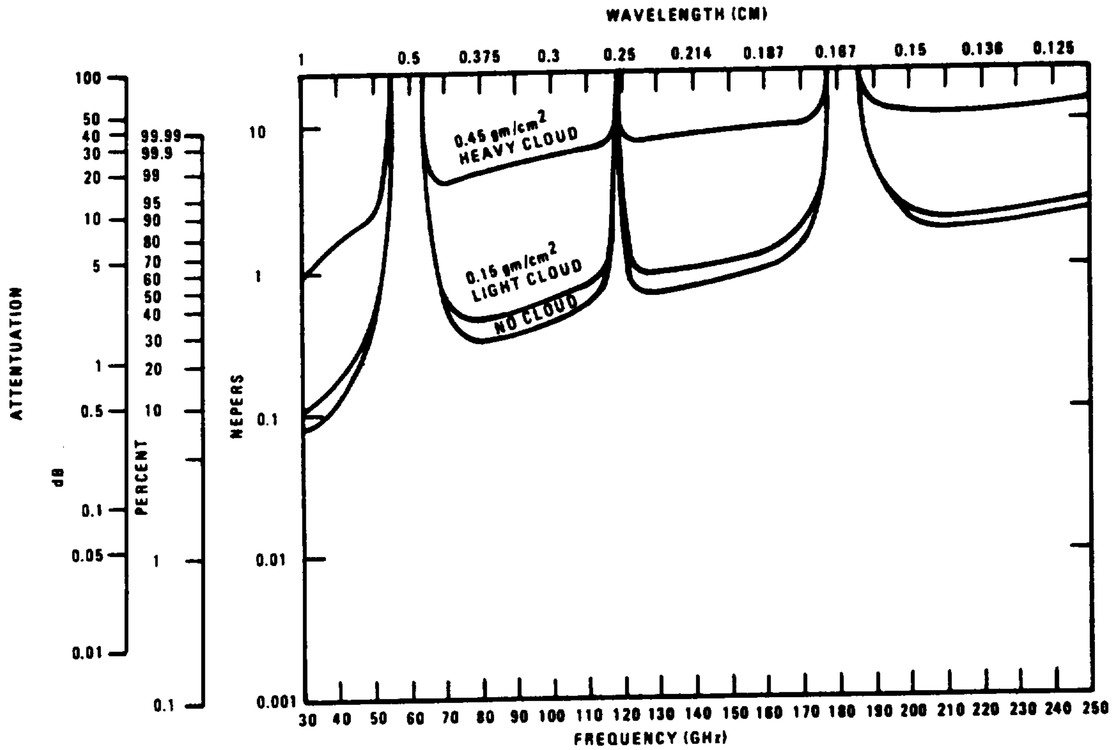

FIGURE 3. ATMOSPHERIC ATTENUATION

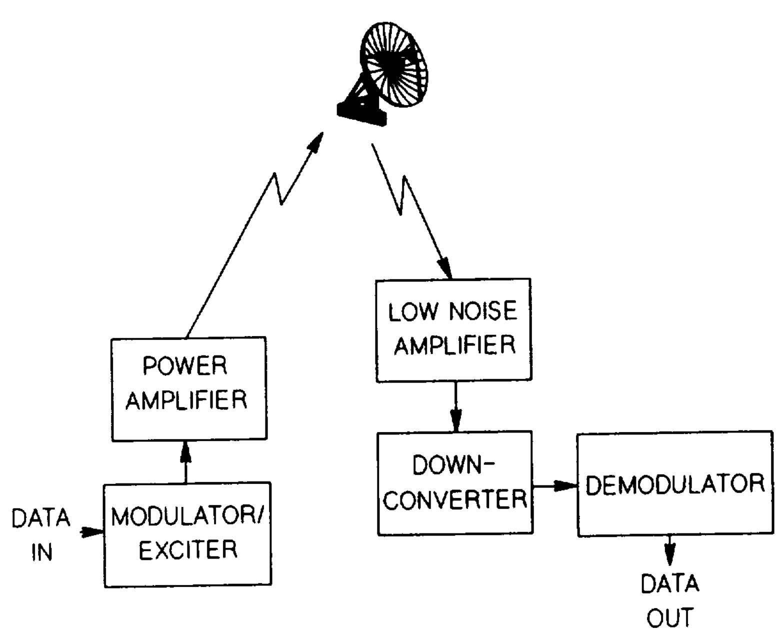

FIGURE 4. MILLIMETER WAVE SYSTEM

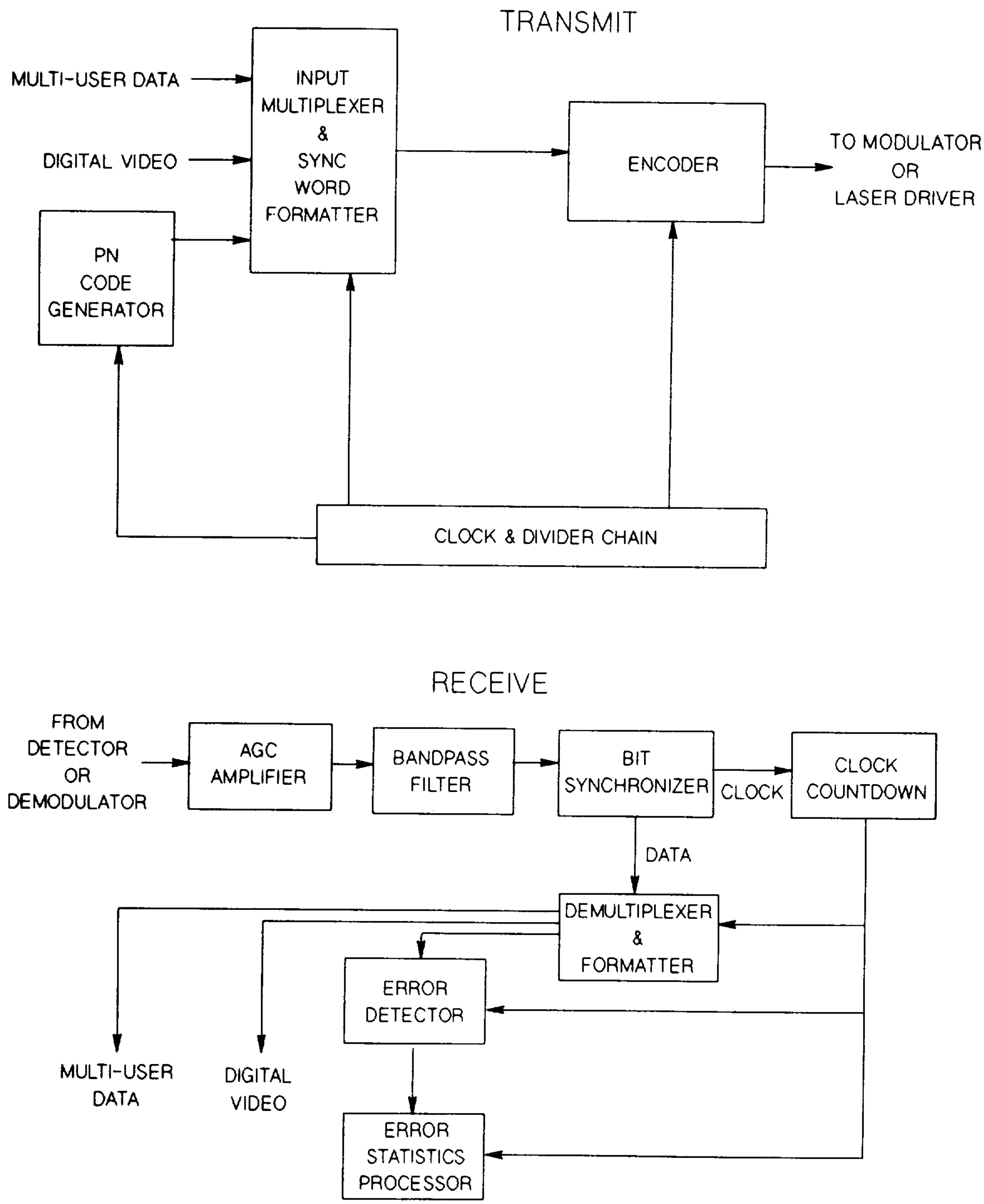

FIGURE 5. TYPICAL COMMUNICATION ELECTRONICS